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A JOURNAL OF EXPERIMENTAL AND THEORETICAL PHYSICS

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BY

EDWARD L. NICHOLS
ERNEST MERRITT, and FREDERICK BEDELL

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IONIZATION PRODUCED BY ENTLADUNGSSTRAHLEN AND EXPERIMENTS BEARING ON THE NATURE OF THE RADIATION.

By Elizabeth R. Laird.

A SHORT time ago the author reported some experiments on Entladungsstrahlen [1] which were largely confirmatory of work done by Wiedemann [2] and by Hoffmann.[3] The results showed that a solid salt solution, $CaSO_4$ + 2 per cent. $MnSO_4$, is made thermoluminescent by the action of a radiation from the spark of a Wimshurst machine or induction coil, that the effect increases with increased capacity or potential difference, that the radiation is propagated in straight lines, as evidenced by shadows, that it is stopped by quartz and other solid substances, that it is not affected by a strong air blast, that it is somewhat more absorbed by carbon dioxide than by air. These experiments have been carried further and experiments have also been made showing that the same agent produces marked ionization in the air, and in other gases and vapors. For convenience' sake the experiments have been grouped in sections.

I. Experiments on the Thermoluminescent Effect.

The general method was the same as that described previously.

1. By using a spark 1.5 cm. long and placing pieces of mica as indicated in the diagram (Fig. 1), and the salt below, it was shown

[1] Phys. Rev., March, 1909, p. 225.
[2] Zeitschr. f. Electrochem, p. 159, 1895.
[3] Wiedemann, Annalen, LX., p. 269, 1897.

that the radiation comes from the whole length of the spark and cannot be due to metallic dust driven from the electrodes, again confirming Hoffmann's work.

2. The spark arranged vertically produced a very sharp shadow of the lower electrode on a plate of salt placed some centimeters below.

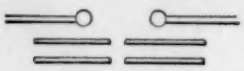

Fig. 1.

3. The effect was not cut off if the salt was placed in a metal box with a metal gauze cover, all of which is earth connected. Hence the effect is not due to direct electrical induction.

4. Aluminum .0004 cm. thick, very thin glass, very thin mica cut off the effect completely.

5. The only solid substance thus far found which transmits the effect is thin celluloid in the form of films made by letting fall a drop of a solution of celluloid in amyl acetate on water. These films when dry transmit the radiation. Placed under the spark of a Wimshurst machine they are easily broken, and in breaking become thicker, so that with this arrangement it appeared as if they too cut off the effect. When however the spark *B* obtained from Leyden jars arranged as in the diagram (Fig. 2), where the spark gap *A* is connected to an induction coil, is used as source of radiation, it is found that one half, or one third, or sometimes a smaller fraction of the effect is transmitted. The length of the spark gap *B* was usually 1 mm.

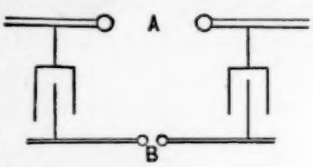

Fig. 2.

6. As these films were so easily broken by the spark, it seemed possible that the thermoluminescent effect might be due to a mechanical pressure wave. It was found however that thin paper or goldbeater's skin stretched over a frame did not transmit the effect. Also if the spark gap was placed around the bend of a tube, the ends of which were closed as indicated in Fig. 3 no effect was produced in 15 minutes exposure on salt placed at the lower opening, although 1 minute direct radiation at the same distance produced some effect. It appeared also that direct mechanical tapping on the salt did not produce thermoluminescence.

II. General Observations on the Ionization Effect.

The ionization produced by this radiation from the spark was observed with the apparatus which is illustrated in Fig. 4. An ionization chamber 5 cm. deep, 8 cm. in diameter, with a window 3.2 cm. in diameter, was provided with a wire electrode connected directly to an ordinary type gold-leaf electroscope. The window was covered with a celluloid film and protected by metal gauze. The

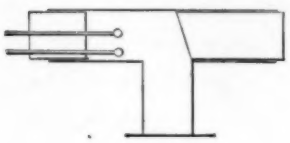

Fig. 3.

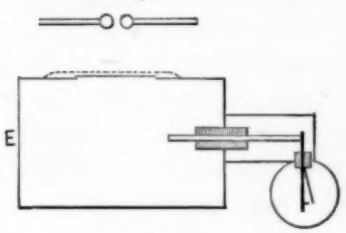

Fig. 4.

gauze and vessel were earthed and the electroscope charged. The leak was observed through a reading microscope. The rate of leak varied under different conditions from 5 to 2,000 scale divisions per minute. At a window distance of 2 cm. from the spark the leak in air was about 20 scale divisions in 20 seconds. It varied with the film used and the functioning of the interrupter. The insulation leak was usually not greater than 0.2 scale division per minute, in some instances it was 1 scale division a minute, only on two or three occasions did it rise higher. To aid in estimating the sensitiveness of the apparatus and magnitude of the results, a thick layer of uranium oxide 9 cm.^{2} in extent, was placed on the bottom of the chamber; the rate of leak was 25 scale divisions per minute.

III. Experiments Showing that the Thermoluminescence and Ionization are Due to the Same Cause.

1. As already mentioned, it is known that increasing the capacity parallel to the spark gap increases the thermoluminescent effect. An experiment was made in which one half of a salt plate was exposed to the spark and the rate of leak in the ionization chamber was simultaneously observed when the source of radiation was the spark of the induction coil used without capacity. Then the other

half of the salt was exposed, and the leak observed when the source was the secondary spark from the Leyden jars. The rates of leak were in the ratio of 1 : 8, the times of exposure 2 minutes and 30 seconds respectively. The half of the salt given the shorter exposure gave a brighter luminescence when heated. If the luminescence had been exactly proportional to the ionization it should have been twice as bright.

2. Both effects are stopped by thin mica, and aluminum, but are transmitted considerable distances through air, and as already stated are transmitted by celluloid films.

3. Both effects are stopped by quartz. In the case of thermoluminescence under conditions when an exposure of 30 seconds gave quite appreciable thermoluminescence, an exposure up to 15 minutes gave no effect when the salts were well heated previously and covered with quartz 0.6 mm. thick. With longer exposures of 25 or 30 minutes some slight thermoluminescence was difficult to avoid, but it seems probable that the slight effect sometimes produced is caused by known light and not by Entladungsstrahlen. In the case of ionization when the bottom of the chamber was not cleaned, results such as follow were obtained, the leak per minute being given.

TABLE I.

Insulation Leak.	Leak (Computed) with Film.	Leak with Quartz.
0	100	1
.8	75	.8
.5	1600	1

4. Both effects are produced by a radiation travelling in straight lines from the spark. The existence of distinct shadows cast on the thermoluminescent salts has already been referred to. To test the same for the ionization effect the apparatus was arranged so that the spark was 2 cm. above the window of the ionization chamber, and a piece of mica of such a size as just to place the window in shadow was put 1 cm. above it. There was no film over the window. The following results were obtained.

Insulation leak	.8 in 1	minute.
Leak, mica in position	1 " 1	"
	2 " 1	"
Leak, mica moved slightly	4 " 1	"
Leak, mica carefully replaced	1 " 1	"

5. Neither effect is altered by changing from brass to aluminum electrodes at the spark gap.

In the case of thermoluminescence, one half of a salt plate was exposed to the spark between brass electrodes, the other half to the same between aluminum electrodes for the same time. The times used varied from 20 seconds to 15 minutes. No perceptible difference was seen in the luminiscence of the two halves.

In the case of ionization the average of a number of experiments witn brass wire electrodes was a leak of 18 scale divisions a minute, with aluminum 17 scale divisions a minute. The difference is not as great as between individual experiments with the same electrodes.

6. Neither effect is altered by a strong air blast placed between the spark and the salt or ionization chamber. In the actual experiment on ionization a slight increase was observed, probably due to the blowing away of absorbing vapors.

7. The cause of both effects is absorbed at least approximately in the same degree by air.

In one experiment on thermoluminescence it appeared that about one half the radiation was absorbed by 6 cm. of air, since at a distance of 9 cm. with nine times the exposure the luminescence appeared only about half as bright as at 3 cm. In another case it appeared as if 2 cm. absorbed a large proportion.

Experiments on ionization gave the leak at a window distance of 2.9 cm. as 50 scale divisions in 6 seconds, and at 6.5 cm. as 50 scale divisions in 70 seconds, indicating an absorption of somewhat over 50 per cent. in 3.6 cm. The absorbing air in this case may have had a trace of turpentine vapor in it.

8. The celluloid films absorb approximately the same proportion whether estimated by the thermoluminescent or the ionization effect. In the first case it was attempted to estimate the proportion directly, also by observing the times during which the thermoluminescence under the film and outside lasted, also by trying to expose one part of the salt plate directly for a time which would give about the same luminosity as a longer exposure through the film. In various cases it was estimated that the film transmitted one fourth to one half the effect.

On a number of different occasions during the experiments on

ionization the electroscope leak was observed with the window covered and uncovered. The times given for the gold-leaf to pass over the same number of scale divisions are given below.

TABLE II.

With Film.	Without Film.
70 seconds.	25 seconds.
33 "	10 "
28 "	15 "
35 "	10 "
60 "	10 "

It will be seen that the ratios vary from $\frac{1}{6}$ to $\frac{1}{2}$ approximately.

9. Neither effect is produced largely by the radiation from the carbon arc.

A salt plate exposed 10 minutes at 6.5 cm. distance was not made thermoluminescent. When the window of the ionization chamber was placed 5 cm. from the arc the known effect of ultra-violet light outbalanced any other, as shown by observing the leaks with a piece of quartz 1 mm. thick, and a celluloid film placed alternately over the window. The ratios were as follows in different experiments $\frac{30}{26}$, $\frac{30}{30}$, $\frac{25}{27}$, $\frac{13}{14}$.

IV. EXPERIMENTS SHOWING THAT THE IONIZATION TAKES PLACE IN THE AIR OR GAS IN THE CHAMBER, AND IS NOT AN EFFECT OF THE METAL ELECTRODE OR WALLS OF THE CHAMBER, NOR OF THE DIFFUSION INTO THE CHAMBER OF IONS FROM OUTSIDE.

1. The leaks whether the electrode is positively or negatively charged are approximately equal if the bottom of the ionization chamber is oxidized, or in such condition that no leak is observed when the window is covered by quartz. The time to pass over 20 scale divisions from 50–30 is given in a variety of cases taken on different days in different conditions, sometimes, with vapors in the chamber. The last two numbers are times taken to pass over 50 divisions.

When, as happened in some later experiments, the bottom of the vessel was cleaned, the leak with the electrode positively charged was greater, but the ratios became appreciably equal if the amount through quartz was subtracted. For example in one case the in-

sulation leak, also the leak through quartz, with the electrode negatively charged was 1 scale division in 60 seconds; the leak through a film was 47–30 divisions in 90 seconds, but with the wire positively charged the same leak occurred in 72 seconds, and the leak through quartz was 4 divisions in 60 seconds. Subtracting the rate of leak through quartz from that through the film it becomes 10.1 and 10.3 scale divisions a minute in the two cases.

TABLE III.

Positively Charged.	Negatively Charged.	Positively Charged.	Negatively Charged.
18 seconds	16 seconds	15 seconds	15 seconds
10 "	10 "	14 "	15 "
3 "	3.2 "	3.5 "	3.5 "
16 "	14 "	14 "	13 "

2. No difference was observed whether a copper gauze electrode or a brass plate electrode of the same size was used. The same leak was obtained when the electrode was placed so as to be entirely shielded from the light of the spark.

3. The films used as windows are not specially photoelectric. Quartz placed over the film cut off the effect just as it did when the film was not there. A film spread over the bottom of the vessels did not increase the effect. A film attached to the electrode, and so to the electroscope, so that the light of the spark would fall on it, acquired no charge when the window was shielded in the usual way, and if initially charged either positively or negatively lost the charge completely.

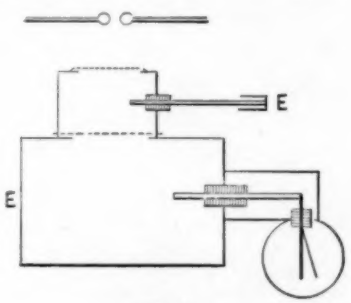

Fig. 5.

4. As already described in III., 6, air blown across the top of the window does not diminish the effect, also the ionization remains as large if the ions are removed above the window in the following way.

The main ionization chamber was placed with its window 6.5 cm.

from the spark. Above it was placed a second similar to the first but smaller, with a window protected by gauze, and an insulated wire electrode connected to a small additional capacity (Fig. 5).

The leak in the lower chamber was then observed when the upper electrode was charged and uncharged. Since the current in the gas appeared to be a saturation current, stopping abruptly when the coil was stopped, the same would be true in the upper chamber. The upper electrode was also connected directly to the electroscope to make sure that the capacity used was such as to keep the electrode charged during the course of an experiment. Below are some of the results.

TABLE IV.

Insulation Leak.	Leak, Upper Electrode Uncharged.		Leak, Upper Electrode Charged.	
	Scale Divisions.	Time.	Scale Divisions.	Time.
.5	50–43	60 seconds	49–41	60 seconds
			50–43	60 "
.5	50–41	115 "	50–41	120 "
	49.5–39	125 "	49.5–39	120 "

The rate of leak is the same in the two cases, hence the ionization observed in the lower chamber is produced there.

5. The same result follows from the fact that the ionization observed depends very largely on the vapor or gas in the ionization chamber. It is difficult to obtain accurate values of the relative ionization produced in different cases, as the celluloid films permit some vapors to pass through, and the effects are greatly influenced by this fact. The substances that show a large ionization in most cases appear also to absorb strongly, and so the actual ionization observed would not be that produced by an incident radiation equal to that in case the air were the only absorbing medium. Another factor rendering difficult the comparison is that very small amounts of vapor change appreciably the ionization, and it was difficult to know when all traces of other vapors were removed. Although the results can be regarded as at most approximations, they are nevertheless given as being interesting.

Illuminating Gas (Coal Gas). — Without moving the ionization

chamber gas was led in to fill it, and the window was covered with a film. The smell of the gas could be detected above the chamber. The leak changed from 40 scale divisions in 18 seconds to 10 sc. div. in 30 secs., but it was found that fanning above the window increased the leak, and putting in less gas to begin with, and fanning the top, the leak rose to 50 sc. div. in 5 secs., $4\frac{1}{2}$ times as large as the leak in air, repeating this several times the largest ratio obtained was 12 times the leak in air. These results are explained if one supposes that the gas absorbs the radiation strongly so that when there is some gas between the window of the chamber and the spark, the radiation entering the chamber is much less intense than when air is the medium, but at the same time the radiation produces more ions in coal gas than in air. It is hoped to repeat these and other similar experiments using a current of air to keep the upper space fairly free of foreign vapors and gases.

Carbon Dioxide. — Solid carbon dioxide was put into the chamber and allowed to partly evaporate before readings were taken. The reading fell at first from 20 sc. div. in 20 secs. to 4 in 60. Fanning the top it rose to 10 sc. div. in 25 secs., and in no case was a value greater than one half that in air obtained.

Turpentine. — It was found incidentally that the presence in the ionization chamber of soft wax, that had been worked by the hands, increased appreciably the leak. This led to trying the effect of placing a few drops of turpentine in the chamber. Very small glass receptacles which could be introduced without disturbing the apparatus appreciably were used for this and other liquids. From 20 sc. div. in 20 secs. the leak rose to 50 in 1.6 secs., making the rate about 30 times that in air. In one case a ratio considerably higher was obtained but more frequently a ratio of about 30.

Ether. — A small amount of ether increased the leak from 30 sc. div. in 30 secs. to 50 sc. div. in 3 secs. or 16 times. Letting a drop fall on top of the chamber the effect diminished to 5 in 25 secs.

Ammonia. — With liquid in the chamber the leak rose from 20 sc. div. in 51 secs. to 20 sc. div. in 9 secs. Removing the liquid, and introducing fresh air above the window, it rose to 43 sc. div. in 5 secs., or 22 times that in air.

Alcohol. — It was very difficult to remove the traces of ammonia

in the chamber, but with the introduction of alcohol the leak rose from 30 sc. div. in 37 secs. to 30 sc. div. in 12½ secs. or increased three times.

Methyl Iodide. — When some drops were put in the chamber the leak increased from 30 sc. div. in 17 secs. to 30 in 7 secs. It was observed however that there was a distinct smell of the vapor above the window. Taking the liquid out of the chamber, leaving vapor in, and fanning fresh air on top, the leak rose to 50 sc. div. in 1.8 secs. or 16 times that in air, which is probably still less than the true value.

Hydrogen Peroxide. — A few drops of a 20 per cent. solution of hydrogen peroxide were placed in the chamber. The window being 6 cm. from the spark the leak rose from 3 sc. div. in 60 secs. to 7 sc. div. in 60 secs.

It seems rather evident from the experiments that the amount of ionization is not directly proportional to the absorption by the vapor or gas of the radiation, as for instance a larger ionization could not be obtained with carbon dioxide than with air. It is evident also that it is not at all proportional to the density. It is hoped to make experiments on the absorption of vapors for this radiation.

V. Experiments Indicating that the Ionization Observed Ordinarily in the Neighborhood of a Spark is Almost Entirely Due to this Radiation.

Experiments have already been described (IV., 4) showing that the ionization observed in the chamber when the window is covered with a film is not due to any diffusion of ions through the film, but that the ions are produced in the chamber itself. Also the experiment showing that a piece of mica casts a shadow in which few ions are found, would show that the ions ordinarily found in an air space some distance from a spark do not reach there by slow diffusion. The following experiment makes the point more clear. The ratio of the leak in the ionization chamber with the window film covered, to that with the window uncovered, varied from one sixth to one half. Putting first one film, then two, then three over the window, readings such as the following were obtained.

1 film 10 scale divisions in 60 seconds.
2 films 5.6 " " " 120 "
3 films 3.5 " " " 120 "

This shows that the ratio of the effect traversing three films to that through two, likewise that through two to that through one, is of the same order as the ratio of that through one film to that through the uncovered window. This is most simply explained if one supposes that each film absorbs a certain fraction of the incident radiation which without any film would therefore produce in the chamber the ionization observed.

VI. Experiments on Reflection.

Since the radiation producing the two effects studied travels in straight lines from all parts of the spark, casting shadows identical in position with those cast by the light of the spark, and since ultra-violet light is known to produce special luminescent effects and according to Lenard[1] to ionize a gas, it was sought to determine if this particular radiation were a kind of light by seeing if it could be reflected. That it is not light of wave-length greater than 1,000 Angström units seems plain from the fact that it is transmitted through at least 10 cm. of air. Such a layer of air would not be much more transparent than quartz in any region above λ 1750, and absorbs completely in the region below that photographed by Lyman.

Hoffmann tried to reflect the Entladungsstrahlen but obtained no result, although at the same distance bright luminescence, he states, would have been produced by direct radiation. It seemed quite possible however that there might be reflection, and yet that the amount reflected would be only a fraction of the incident radiation. Using thermoluminescence as a detector of the radiation, a polished silver surface, made by polishing the back of a plate glass mirror from which the shellac had been removed, was used as a reflector. The first arrangement was as indicated in Fig. 6, where B is the spark gap, M the mirror, S the salt, and A a piece of mica placed to shield the salt from direct radiation. When one minute would have produced some luminescence for the same direct distance through air, in a large number of trials only once did there seem to be any reflection for

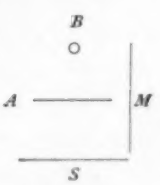

Fig. 6.

[1] Annalen der Physik, IV., 1, p. 486, 1900.

15 minutes exposure. Putting a willemite screen in the same position as the salt, however, it was apparent that the fluorescence was much less than would have been produced at the same distance without reflection.

Another arrangement of the apparatus was then made, which permitted the distances used to be made smaller. The salt was placed at one side a few millimeters above the spark, thus placing it in shadow with respect to the direct light. The mirror was placed above and as close as possible. Still up to twelve minutes exposure no effect was observed, at fifteen minutes in one case a faint light lasting about one second was seen, while the luminescence produced by direct radiation of five minutes lasted during one hundred seconds. In the hope of making it easier to detect any faint reflection a piece of paper with a rectangular hole in it was placed over the mirror, so that the more intense patch of light reflected, as indicated by the effect on a willemite screen, was sharply bounded. Exposures of twenty-five to thirty minutes were given. Unfortunately it was found that in several of the experiments made in this way the salts used were more than ordinarily affected by light. In the other trials either there was no certainty of any thermoluminescence, or the faint luminescence seen had not the shape of the rectangular patch as expected. In the cases where more light was seen and an effect could also be seen under quartz, the light patch was fairly rectangular. On account of the difficulty in keeping salts that would not be affected by light in this long exposure so near to the spark, this particular method was abandoned for the time being in the hope that more would be obtained by the ionization method.

To test for reflection by this method the ionization chamber was placed somewhat to one side of the spark, and the window was screened from direct radiation by a piece of mica. The mirror was placed above the spark, with its reflecting surface downwards and slightly slanted so as to throw a good light on the window. The insulation leak was taken, then the leak with the coil working without mirror, and with mirror alternately. A steady leak of .4 or .5 scale division per minute was obtained with the mirror in position, when the leak without the mirror but with the coil working, measured

over 4 or 5 minute intervals was not greater than .1 scale division per minute. It was found, however, that as nearly as could be estimated the same leak was obtained if the shellacked end of the mirror was used or if the glass surface was used as reflector. It was not easy to measure the distance through air which the radiation had to travel, but at approximately the same distance the leak was 20 scale divisions a minute. Leaving the chamber in position and removing the mica screen the leak was 46 scale divisions a minute. This would mean that a fraction not greater than one fortieth of the radiation was being reflected. The amount was so small absolutely, that although the leak was regular it seemed not quite evident that it was due to a special sort of Entladungsstrahlen. When, however, the effect of vapors on the amount of ionization was discovered, it seemed easy to test, as the presence of these vapors did not increase any leak due to ordinary light, and would not increase a leak due to the diffusion of ions.

Accordingly an experiment was made in which the leak without mirror was first taken, which was small as before, then with mirror in position, when a leak of 1.8 scale divisions per minute was obtained. Then turpentine was put in and the leak went up to 30 scale divisions a minute at once, and later, with some rearrangement, to 150 scale divisions. This seemed to make it clear that the leak observed was due to a special radiation, and again quartz cut off the leak.

To find the approximate ratio between the amount of ionization obtained in this way and from the direct radiation an experiment was made with considerably less turpentine vapor present. The leak with current and without mirror was 1 scale division per minute, with mirror 22 scale divisions per minute, and at the same distance through air the rate was 500 scale divisions per minute. This would indicate the fraction reflected as about one twenty-fifth. With the same arrangement the angle of the mirror was altered to throw less light on the window of the ionization chamber. The leak fell to 6 scale divisions per minute. This appeared to indicate that the ionization was due to a direct reflection.

In order to test this further, experiments were made as follows, The mirror placed horizontally, was moved from a position where

no light was reflected, to one where the window was partly in light, and then in full light. The movement was through 1 cm. each time. The insulation and direct leak being 1.4 scale divisions per minute, the readings were 1.4, 7.8 and 29 scale divisions per minute. Again with positions of the mirror edge 0 cm., .5 cm., 1.3 cm., 1.5 cm., from the spark, the following rates of leak were obtained, 102, 107, 15, 10 scale divisions per minute. In this case the film was found broken, and the direct leak without mirror was 5 scale divisions per minute. At the position 1.5 cm. the window appeared in shadow, and at .5 cm. in full light. In another experiment the mirror was slanted so that a smaller motion would change from the position of full illumination of the window to that of little or none. In this case with a motion of a few millimeters each time towards a position of no reflection, the rates of leak were as follows: 11, 6, 0, 2 scale divisions per minute. The leak did not fall to zero at exactly the point expected but did so nearly so, that the radiation appeared as if directly reflected.

On the other hand it has been already mentioned that different surfaces reflect about equally well. With the mirror horizontal a number of different surfaces were placed on it, and the rates of leak were observed as follows.

Glass	18	scale divisions	per	minute.	
Cardboard	12	"	"	"	"
Paper	20	"	"	"	"
Copper, unpolished	20	"	"	"	"
Lead	23	"	"	"	"

These results are rather remarkable, and the writer hopes to experiment further to test if the apparently reflected radiation is of the same quality as the incident or if it is a kind of secondary radiation. These experiments explain the difficulty experienced in obtaining a reflection when the thermoluminescent method was used, as the paper used to cover all but a portion of the mirror would reflect almost equally with the mirror itself. A general luminescence should have been looked for and not one bearing a resemblance to the rectangular patch of light seen on the salt. It is worth while, perhaps, to note that the light producing fluorescence in willemite is reflected quite differently from paper and silver, as in the above

case the fluorescence on the willemite screen was rectangular, corresponding to reflection from the mirror itself.

VI. Some Additional Experiments on Ionization.

The effect of turpentine vapor on the ionization was so great, that it was thought it might be due to some chemical action and be connected with the action of turpentine vapor on ozone. That the ionization is not directly due to the formation of ozone was shown by the following experiment. A piece of potassium iodide starch paper was placed in the chamber rather close to the film and exposed to the spark a certain time. Then another piece was exposed in the same position but with quartz over the window instead of the celluloid film. The paper showed slightly more darkening under the quartz than under the film.

It was found also that whether an appreciable leak was observed with a quartz window, or not, it was not increased by the presence of vapors. Thus on one occasion the leak through quartz was 5 scale divisions in 60 seconds, adding turpentine the leak was 50 scale divisions in 3½ seconds through a film, but 4 scale divisions in 60 seconds through quartz. With methyl iodide vapor, when the leak with a film window was 50 scale divisions in 1.8 seconds, with a quartz window it was 1 scale division per minute.

It was further found that with a stream of coal gas flowing through the chamber, in which was a little turpentine, an ionization effect was still observed, the leak being 8 scale divisions in 60 seconds. That it was not larger is evidently due to the fact that the air above the film was so impregnated with coal gas that a large portion of the radiation was absorbed before reaching the chamber.

Attempts were made to see if soap films could be made which would transmit this radiation. A leak of from .5 to 1 scale division per minute was obtained with the window covered with a film showing colors, made from a solution to which a little glycerine had been added, but this leak was not increased by the presence of turpentine vapor.

From the preceding experiments it is evident that there is a radiation from the spark in air, at atmospheric pressure, which pro-

duces thermoluminescence in certain salts, and ionizes the gas through which it passes, and that it is not mechanical in its nature such as particles driven from the electrodes or a pressure wave. That it is not of the nature of α or β rays, or neutral pairs shot off from the spark appears evident when it is considered that this radiation passes through 10 cm. of air, and yet is stopped by very thin aluminum. This is quite contrary to the behavior of material particles moving with high velocities. It is evidently not light of wave-length greater than 1,000 Angström units, the limit of the spectrum photographed by Lyman, since in the known regions quartz is everywhere comparable in transparency with air.

The question whether this radiation may be light of extremely short wave-length, or soft Röntgen rays, is exceedingly interesting. Lenard found that ultra-violet light in the region studied by Schumann and by Lyman would produce ionization in a gas, and it would seem plausible that light of still shorter wave-length should act more vigorously. Since in the known region of the spectrum small amounts of substances sometimes affect the transmission enormously, one need not be surprised at the large effect of various vapors on the ionization if light were the cause. The existence of shadows and of reflection would also be directly explained. On the other hand, the fact that the results are independent of the material of the electrodes, when all known light effects, including the ionization observed by Lenard, vary greatly with different materials is a reason for thinking the effect more electrical in its origin, in the sense of being independent of the particular atom. Theory leads one to expect a sort of soft Röntgen radiation from a spark due to the accelerated or retarded motions of ions, and this explanation of Entladungsstrahlen has already been given.[1] Such radiation would probably be increased in intensity by additional capacity, it also would travel in straight lines, one would expect it to produce ionization. It might seem remarkable that the ionization produced by such a radiation should vary so greatly with different vapors. Experiments show, however, that the ionization produced by X-rays from a soft tube is not at all proportional to the density. Strutt[2] gives the ionization in methyl iodide as 72

[1] J. J. Thomson, Conduction of Electricity through Gases, p. 603.
[2] Proc. Roy. Soc., 72, p. 209, 1903.

times that in air at the same pressure. The radiation in question would be softer than that from any tube; it is probably absorbed 80 per cent. by 10 cm. of air, as compared with one per cent. for radiation from a tube; and it might reasonably be concluded that the ionization produced by it would bear little relation to the density of the substance traversed. If the penetrating power and lack of reflection in X-rays is due to the thinness of the pulse, here, where the change in the motion of the ions is less rapid, the pulse would be less thin, the properties would be somewhat altered, and an explanation of the apparent reflection and the absorption by thin aluminum and other substances might be found.

Facts bearing on the penetrating power of the radiation might enable one to distinguish between the hypothesis of a light radiation and a soft Röntgen radiation, as the cause of the effects noted. Light of a given wave-length would have a constant coefficient of absorption whatever its source, whereas Röntgen rays produced under various conditions, have different penetrating powers. Sir J. J. Thomson[1] found some years ago that ionization was produced near the spark, but since at atmospheric pressure the ionization chamber had to be placed within 1 cm. of the spark for an effect, it did not seem clear that the ionization observed was due to a special radiation, and there seemed a possibility that the same observed at lower pressures was due to known ultra-violet light. When one adds however to these experiments the writer's observation that with a small induction coil a layer of 2 cm. of air produced a large absorption, and that using a larger coil with capacity, 5 cm. produced perhaps no more, and when one notes that Hoffmann with a very large Wimshurst machine observed still less absorption, one is led to think that there is a radiation here of different penetrating power depending on the circumstances of production. To these facts relating to penetrating power should be added the observation o Hoffmann, confirmed at a pressure of about 2 mm. by the writer, that with diminishing pressure the radiation gains the power of penetrating and affecting a photographic plate. It is not yet proved beyond doubt that it is the same quality of radiation in the two cases, but that seems most probable. In that case the properties

[1] Proc. Camb. Phil. Soc., X., p. 74, 1899.

of "Entladungsstrahlen" would ally them very closely to soft Röntgen rays.

In conclusion the writer desires to express her thanks to Prof. Sir J. J. Thomson who made it possible for her to carry out this investigation at the Cavendish Laboratory.

Mount Holyoke College.

RELATION BETWEEN TEMPERATURE OF ELECTRODES AND VOLTAGE OF THE ELECTRIC ARC.

By C. D. Child.

THE theory of the electric arc, as at present held, leads us to expect that with cooled electrodes a higher potential difference will be needed to maintain the arc than with electrodes not cooled, but the experimental evidence to a large extent favors the opposite view. It, therefore, seemed worth the trouble to review what has been done on the subject and to repeat some of the experiments.

Résumé of Previous Experiments. — It may first of all be stated that phenomena which bear indirectly on this subject lead us to expect that the arc will be maintained more easily when the terminals are hot than when they are cooled. For example, if the terminals of the arc are separated for some distance when it is first started, the arc is more apt to go out, than it is, if the terminals are allowed to become hot before being separated, as if heating the terminals allows the current to flow more easily.

Again it is much more difficult to maintain an arc in hydrogen than in air, and this has generally been explained as being due to the fact that hydrogen cools the electrodes more rapidly than air, as if cooling the electrodes made necessary a greater potential difference.

When we come to the more direct evidence we find that many of the earlier experiments are of little value.

Such for example as that of de la Rive [1] who attempted to heat the arc by placing an alcohol lamp under it. There would be three results produced by this experiment other than the one which he had in mind. First, the flame would probably cool the carbons of the arc instead of heating them. Secondly, the flame would blow

[1] Archives de l'Electricité, 1, 262, 1841.

the arc out of its original shape, and thus cause a greater drop in potential through it. Lastly, the gases of the flame would change the character of the arc and this might have a very appreciable effect on the voltage.

Tommasi[1] formed an arc between copper tubes, and found that when they were cooled by passing water through them, the arc was very unsteady and the luminosity became less. This is one of the most satisfactory methods of examining the question, but his results are not as definite as is desired.

Cross and Shepard[2] endeavored to heat the electrodes by protecting them from convection currents. This method is more satisfactory than some, and yet it is conceivable that the protection would alter the character of the gas sufficiently to change the potential difference.

They cooled the anode by surrounding it with a water jacket. This method would be entirely satisfactory providing no water vapor was allowed to pass into the arc. This experiment has been repeated by myself and will be discussed further in connection with that work.

Lecher[3] used three methods for changing the temperature of the electrodes. The first was to warm the electrode with a gas lamp, which we have already seen is open to serious objection. The second method was to wrap fine copper wire about the electrodes, his idea being that the wire would cool the carbon, since it had greater thermal conductivity. It is not, however, self evident that it would do this, for even if the copper had infinite conductivity, it would not cool the carbon unless it was able to get rid of the heat at the surface faster than the carbon does, and one cannot be certain that it would do this. There is also the possibility that the copper would be heated sufficiently to send some of its vapor into the arc, and this would, no doubt, decrease the resistance of the arc.

The third method which he used was to cool the electrode by immersing it in a mercury bath, which was in turn kept cool by running water. This would apparently be a suitable method, providing that the mercury vapor did not pass into the arc. If it should, it would be expected to lower the resistance of the arc.

[1] C. R., 93, 716, 1881.
[2] Proc. Amer. Acad. Sc., 22, 227, 1885.
[3] Wien. Ber., 95, II., 992, 1887.

This experiment was also repeated by myself and will be further considered in connection with the account of that work.

The experiment of Hertzfeld[1] where he blew cold CO_2 into the arc was valueless, for the reason that the change in the character of the gases and the distortion of the arc by blowing into it would produce far greater effects than those produced by cooling the electrodes.

Schultze[2] used the same method as that of Tommasi. He experimented with the arc between copper electrodes which could be cooled by passing water through them. He found that cooling the cathode raised the potential difference about one volt, cooling the anode raised it about four volts, and cooling both electrodes about six volts. Where an oxide is formed by the action of the arc this effect was not found. Even with iron the effect could not be shown. This was partly due to the smaller heat conductivity of the iron.

Mitkiewitz[3] found that a current of 2 amperes could be passed through an arc with a potential difference of only 2 volts if the anode was heated in an oxy-hydrogen flame. But it is a question whether this is an arc at all and not merely the discharge produced by a hot flame.

Stark and Cassuto[4] cooled the electrodes by placing a small quantity of the substance to be examined on the top of a water cooled jacket. They were unable to determine with certainty any change when carbon electrodes were used. With copper electrodes they found the voltage much lower when the arc was several millimeters long and no change when it was 2 mm. long. From this they concluded that with still shorter lengths the voltage would be higher with hot electrodes and that the sum of the anode and cathode drops is greater with hot electrodes than with cold ones.

Malcolm and Simon[5] using copper electrodes and small currents with arcs 4 mm. long found that the cooled electrodes required higher voltages. With currents varying from .4 to 1 ampere the voltage was from 20 to 5 volts higher when the anode was cool

[1] Wied. Ann., 62, 442, 1897.
[2] Ann. d. Phys., 12, 837, 1903.
[3] Beib., 29, 739, 1904.
[4] Phys. Z. S., 5, 267, 1904.
[5] Phys. Z. S., 8, 478, 1907.

than when both electrodes were hot, and 40 to 10 volts higher when the cathode was cooled.

Of the experiments, therefore, which are least open to objection there are two sets, and these two arrive at directly opposite conclusions. Cross and Shepard using carbon electrodes came to the conclusion that cooling the electrodes lowered the required voltage, while Schultze, Stark and Cassuto, and Simon and Malcolm using copper electrodes reached the conclusion that cooling the electrodes raises the required voltage. It therefore seemed worth while to repeat some of these experiments and to find the cause of the discrepancy.

Electrodes Cooled by Water-jacket. — The experiment of Cross and Shepard was first repeated. One of the electrodes was surrounded by a copper jacket through which water could be passed. This was made to fit tightly around the carbon, so that no steam could get into the arc. The top of the carbon extended between 1 and 2 mm. above the top of the jacket which was made out of sheet copper, so that the water would come as near as possible to the top of anode. The carbon was 12 mm. in diameter.

The arc was started without any water in the jacket and allowed to run as long as possible without overheating the apparatus. It was then cooled by passing water through the jacket. The potential difference at the terminals of the arc was taken before the anode was cooled and again immediately afterwards. The water was then allowed to flow out of the jacket and the potential difference again noted.

When the cathode was thus cooled there was an increase in the potential difference of 2 or 3 volts. When the temperature increased on drawing off the water there was a decrease in voltage of about 1 volt. It was to be expected that the decrease would not be as large as the increase, since the potential difference would gradually increase due to the burning away of the electrodes.

This change was found to be practically the same for currents varying from 8 to 20 amperes and for lengths varying from 1 to 5 mm., as long as the arc was quiet. With the hissing arc it was difficult to detect any change when the jacket was filled with water.

When the anode was cooled, no definite change could be detected,

but this may have been due to the difficulty of performing the experiment properly. The anode was so hot that it began to melt the jacket if the arc ran for more than a few seconds without being cooled. This may be remedied by raising the carbons further above the jacket, but then the water has no effect on the temperature of the carbon.

Practically the same effects were observed with solid and with cored carbons, but with a mineralized carbon, such as is used in the "flaming arc," no effect could be definitely determined.

These results are opposite to those found by Cross and Shepard, and to find the cause of the difference the experiment was again performed, but with the water vapor passing freely into the arc. For this purpose the electrode was placed in a water jacket having no top, the arc being just above the surface of the water when the jacket was filled. Under these conditions it was found that filling the jacket with water always caused the arc to go into the hissing form, and with this change there was, of course, a large decrease in the voltage. If the arc was hissing before the water was passed into the jacket, cooling the anode apparently had no effect. It is possible that the decrease in voltage which Cross and Shepard found was due to the change to the hissing form of the arc and not to the change in the temperature of the electrodes.

This same experiment was then repeated, using mercury instead of water to cool the electrode as was done by Lecher. A jacket with open top was used so that the vapor of the mercury could pass into the arc freely. It was found that there was a decrease in the potential difference of 10 or 15 volts, when the mercury reached the hot part of the anode.

That this was due to the passing into the arc of mercury fumes was shown by the fact that the mercury lines began to appear in the spectrum of the arc even before the decrease in the potential difference, and became very prominent at the time of this decrease. It was also shown by placing a jacket about the lower carbon which was covered with sheet iron. The carbon was fitted tightly into the opening in the sheet iron. With this arrangement the effect was the same as when the carbon had been cooled with the water jacket, namely, there was a slight

increase in voltage when the arc was cooled and a slight decrease when it was allowed to rise in temperature.

Hollow Carbons Cooled by Flow of Water. — As far as I have been able to learn, the method employed by Tommasi and by Schultze with copper electrodes has not been used with carbon electrodes. It, therefore, seemed worth while to try their method with such electrodes. The arrangement of apparatus is shown in Fig. 1. The arc is formed between a cored or solid carbon *B* and a hollow carbon *C* which was connected to a water faucet so that it could be cooled by running water through it. *V* is a Weston voltmeter for measuring the potential difference between the carbons. *A* is a Weston ammeter for measuring the current. *D* is a 110-volt dynamo. *R* is a variable resistance.

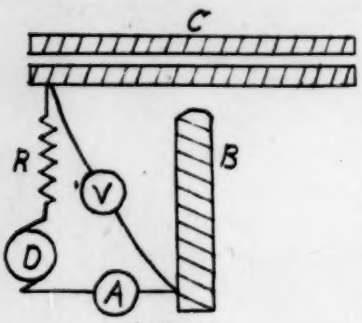

Fig. 1.

Effect of Cooling Cathode. — In the first experiments the hollow carbon was used as cathode. It was found that the voltage always rose when the cathode was cooled. On stopping the flow of water the voltage diminished, but did not come entirely back to its original value, due to the burning away of the carbons. The change in voltage occurred, as nearly as one could tell, at the same time as the change in the luminosity of the cathode.

In the first experiments the outer diameter of *C* was 12.5 mm., the inner 4 mm. The diameter of carbon *A* was 10 mm. The potential difference was approximately 55 volts and the current 8 amperes. In this case the increase in potential difference varied from 3 to 6 volts. The average of ten readings was 4.5 volts. The average of ten readings for the decrease when the flow of water had stopped was 1.8 volts.

The change in the voltage appeared to be the same for currents varying from 6 to 15 amperes, but increased somewhat as the length of the arc was increased from 2 to 10 mm.

Effect of Cooling Anode. — The change in potential difference is not so great when *C* is used for the anode. It is also more difficult

in that case to make satisfactory readings. The arc does not become steady until a crater is formed on the anode and by the time this is done a hole is apt to be burnt through the carbon, so that water flows directly into the arc. But as near as could be determined the potential difference increased about 2 volts on cooling the anode, decreasing nearly the same amount on allowing it again to become heated.

The variation in the voltage appeared to be the same for currents varying from 6 to 15 amperes, but increased somewhat as the length of the arc was increased from 2 to 10 mm.

With the hissing arc the effect was much smaller and so irregular as to make accurate measurements impossible. There was apparently an increase of 1 or 2 volts on cooling the cathode and a decrease of something less than 1 volt on allowing it to again become heated.

With thicker carbons the effect was, of course, smaller. Thus with carbons having an outside diameter of 16 mm. and an inside diameter of 4 mm. the largest increase was 2 volts. With an outside diameter of only 10 mm. and the same inside diameter the effect was somewhat greater than that given above.

Objection may perhaps be raised against this method due to the fact that the carbon was porous. It is conceivable that steam passes through the carbon and changes the arc by the introduction of a different gas. To test this, steam instead of water was passed through the hollow carbon. This was under a pressure of 5 cm. of water, and might have been expected to have a greater effect than the water, if the effect was due to the passing of the steam through the carbon; first, because the steam was under pressure, while the water was not, and secondly, because the carbon was red hot with the steam and it is more porous when hot than when cold. But it was found that the passing of the steam had no appreciable effect on the arc.

The second test was made by inserting a hollow copper tube within the carbon rod. This would keep any water vapor from coming into contact with the carbon, but it also protected the carbon from the cooling effect of the water. However, there was an increase in voltage each time that the carbon was cooled. This was approximately 2 volts.

Effect of Heating Electrodes. — A second method of studying this problem is to heat the electrode C by passing an electric current through it. For this purpose a small carbon 3.3 mm. in diameter was used. It was found, however, that when the current was sent through this carbon, the magnetic field about it deflected the arc. This caused the voltage to be higher and also made the arc unstable, so that any effect produced by heating the carbon was masked by the other change.

Pressures of the surrounding gas as low as .1 mm. were also tried with this method, and while the magnetic effect was then less troublesome, it was still impossible to determine whether there was any effect due to the heating of the electrode or not.

Change in the Cathode and Anode Drops. — In the explanation of the arc commonly given today[1] it is claimed that the fundamental difference between the arc and other forms of discharge through gases is that in the arc the hot cathode allows the electricity to pass from it with great ease. To do this the cathode must have a high temperature and to produce the high temperature there must be an expenditure of electrical energy in its neighborhood. The rate at which this is done equals the cathode drop times the current. It is natural to expect that if the cathode is cooled artificially, it will require a greater expenditure of energy to maintain the needed temperature, and to do this with a given current the cathode drop must be greater. Similarly with any method of heating we should expect the cathode drop to be less.

To test this view, the cathode drop was examined by inserting a carbon pencil 1.7 mm. in diameter between the electrodes of the arc and connecting this through a voltmeter to the cathode. The arc was approximately 4 mm. long and the exploring electrode was placed as near the middle of the arc as possible. The potential difference measured in this way included both the cathode drop and half of the fall of potential through the vapor of the arc, but the method answers for getting an approximation to the cathode drop. Contrary to what had been expected, it was found that there was but a small change in the value of the cathode drop when the cathode was cooled. The anode drop was then examined and it was

[1] PHYS. REV., 19, 126, 1904.

found that there was here a large change. In one case the total potential difference changed from 41 to 47 volts, the cathode drop from 6 to 7 volts and the anode drop from 35 to 40 volts. It is evident from this that the change in potential produced by cooling the cathode does not all occur near the cathode. On the contrary it would appear that the change in different parts of the arc is roughly proportional to the potential existing before the cathode was cooled.

In order to test this view a shunt was placed about the arc and a point on this which had the same potential as that of the exploring pencil was connected to it through a voltmeter. While this connection was made, the cathode was again cooled. At times when this was done the voltmeter would give no reading. At other times there was a small reading in a direction indicating that the ratio of the increase to the original value was slightly greater in the cathode drop than in the remaining part of the arc, but it could be said that the change in the different parts of the arc is nearly proportional to the original potential.

While this was contrary to what I had expected, it is not difficult to explain the phenomena observed. It was thought that extra energy would be developed near the cathode, so that the temperature in its immediate neighborhood would be the same as before. It would appear that what really happens is that the bright spot on the cathode is not as hot as before and that fewer ions pass into the vapor of the arc and consequently its conductivity is less.

This view is also in agreement with the fact mentioned above that the change in potential was found to be greater when the arc was long than when it was short. It apparently follows from this that the anode drop itself depends on the ions produced at some distance from it. There are other facts which would indicate the same. For example the anode drop becomes very much smaller when a salt is placed in the cathode, or when the cathode is a metal instead of a carbon.

Effect of Heating Anode in Mercury Arc. — Stark, Retchinsky, and Schaposnikoff[1] found that with a carbon anode in a mercury arc the anode drop was much smaller when the anode was cold than when hot. It varied in their experiment from 12.4 volts when

[1] Ann. d. Phys. 18, 247, 1905.

the carbon was bright red to 4.7 volts, when it was non-luminous. In the experiment described above there was but a very small change produced by cooling the anode. Because of the difference in these results, their experiment was repeated with the conditions as nearly as possible the same as those described by them.

While a small increase in the anode drop was at times found to accompany a rise in temperature of the anode, it was one of only two or three volts, and it was not possible to show definitely that it was due to the increase in temperature and not to an increase in the pressure of the gas. Ordinarily a carbon rod when heated in a vacuum gives out a large quantity of gas and absorbs some of this again on cooling. Under certain conditions a slight change in the pressure of the gas will produce a large change in the value of the anode drop, and I was not able to find any change in the anode drop when there was no change in the pressure.

This, however, would not explain the results of Stark, Retchinsky and Schaposnikoff for in their experiments the tube containing the arc was not connected to the pump after the arc was started. There was a rise in the pressure of the mercury vapor and the increased amount of vapor *cooled off* the anode so that it became non-luminous. So that with the increase in the amount of pressure there was a decrease in the temperature of the electrode and a decrease in the anode drop. As far as the relations between the pressure and the anode drop, and between the pressure and the temperature of the anode are concerned, this was exactly opposite to that found by myself. I cannot but feel that it would be well if their experiment could be again repeated and more exact measurements made of the various related quantities.

Summary. — A few of the experiments which have been tried by others for the purpose of finding the effect on the electric arc produced by cooling the electrodes were repeated with some modifications and it was shown that cooling the cathode of a carbon arc raised the voltage several volts. There was a smaller increase in the voltage when the anode was cooled.

The anode and cathode drops were measured and both were found to increase when the cathode was cooled, the principal increase being in the anode drop. The increase in the potential in

different parts of the arc was approximately proportional to the potential existing before the cathode was cooled.

Part of this work was done in the physical laboratory of Cornell University, and I desire to express my thanks to Professor Nichols for the privilege which was given me of working in that laboratory.

COLGATE UNIVERSITY,
October, 1909.

NOTE ON WATER OF CRYSTALLIZATION.

BY W. W. COBLENTZ.

IN previous papers[1] on this subject the writer has shown that in substances containing "*water of crystallization*," or "*water of solid solution*" the absorption bands coincide with those of water in its free, liquid state. On the other hand, substances which contain "*water of constitution*" (*i. e.*, the constituents which form water when the substance is heated to a high temperature) do not show absorption bands of water, except hydroxyl groups, which show a band at 3 μ.

The spectroradiometric analysis does not appear to distinguish between water of crystallization and water of solid solution. The absorption bands are identical in position and perhaps in intensity. There are, however, other physical and chemical tests which show a marked distinction between these two forms.

In the process of crystallizing water may enter the substance in varying proportions; but there is a fixed proportion corresponding to a definite compound that is homogeneous and has definite physical properties.[2] On dehydration, the substance becomes inhomogeneous — copper sulphate being a good example. The water escapes at one or more fixed temperature points (and continues to go off at such fixed temperatures until all water is given off) with a sudden change in its properties. On the other hand, in a substance containing water of solid solution or dissolved water, the water is given off gradually throughout a range of temperatures, the physical properties varying with the change in composition. Since there is no loss in homogeneity, and since the water is lost gradually throughout a range of temperatures it cannot be chemically combined. The phenomenon is supposed to be molecular, while in

[1] Coblentz, PHYS. REV., Vol. 20, p. 252, 1905; Vol. 23, p. 125, 1906. Jahrbuch der Radioaktivitat und Elektronik, 111 Band, Heft 4. Carnegie Publication, No. 65.

[2] See a clear and concise summary of a recent paper on this subject by Zambonini, given by Professor Hillebrand in Chemical Abstracts, 3, p. 412, 1909.

the crystallization process the behavior would be atomic in its action in order to form a true compound. This leaves an outstanding difference in the interpretation of the various observations which remains unexplained; for the spectroradiometric observations indicate that, both in compounds with water of crystallization and in those of solid solution, the water is present (*i. e.*, has the same physical properties to heat waves) in the same condition as water in its free, liquid state. Selenite, for example, shows the composite spectra of anhydrite ($CaSO_4$) and of water (H_2O); similarly for opal (quartz + water) which is a solid solution. It has been found that the absorption spectrum of a compound is not the composite of the spectra of the constituent elements (*e. g.*, the spectrum of HCl is not the composite of the absorption spectra of H and of Cl, etc.). How then are we to interpret observations on crystallization products? These differences need not disconcert us, for the spectroradiometric test is continually finding new phenomena needing explanation, the most important, perhaps, being the question of density. Ångström[1] has shown that water vapor is more transparent than the liquid phase, when in such layers that the thickness is inversely proportional to the density of the existing phase. A familiar example is (atmospheric) water vapor which transmits the sun's radiation[2] to 11 μ while a layer of water about two centimeters thick, which is equivalent to the water vapor in the atmosphere, absorbs everything beyond 1.2 μ. Recently he has shown[3] that the absorption of the same quantity of CO_2 varies with the pressure, and that if, when under reduced pressure, an inert gas (*e. g.*, hydrogen) is introduced in such quantities that the original pressure is restored, then the absorption bands of the CO_2 increase to their original intensity. These facts are of interest in connection with the experimental data on tremolite given on a subsequent page. In previous work the writer failed to detect water in amphiboles which generally contain a few per cent. of dissolved water. Through the kindness of Dr. E. T. Allen, of the Geophysical Laboratory, an opportunity was granted to examine several samples of tremolites in which he found

[1] Ångström, Ann. der Phys. (3), 39, p. 267, 1890; (4), 6, p. 163, 1901.

[2] See Carnegie Publication, No. 97, p. 143.

[3] Ångström, Arkiv for Matematik Astronomi och Fysik, 4, No. 3, 1908. Eva von Bahr, Ann. der Phys. (4), 29, p. 780, 1909.

about 2 per cent. of water[1] which is present in solid solution. The sections of the mineral were chosen of sufficient thickness to insure detecting the water, provided its absorption is as great as in the free liquid phase, but as will be noticed presently no water bands could be detected. Its behavior is therefore somewhat like the highly attenuated water vapor in our atmosphere. The bolographs made by Langley[2] show these water bands to be complex and probably shifted slightly towards the short wave-lengths. They show wide absorption bands of water at .92 μ and 1.1 μ which in the liquid are not measurable until the layer has attained a length of about a meter, as shown by Abney and by Julius.

In the present spectroradiometric examination of minerals, a bolometer and fluorite prism were used. The dispersion is much

WATER (H_2O).

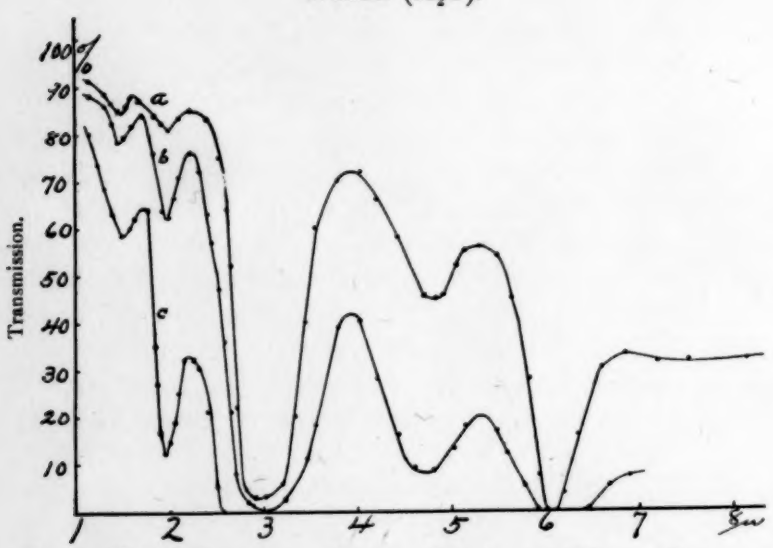

Fig. 2. Water. Curve a; $t = .014$ mm. Curve b; $t = .038$ mm. Curve c; $t = .31$ mm.

larger than in previous work, so that the absorption bands are much wider than previously found. (See selenite, Fig. 2, and the same specimen described in Carnegie Publication 65, Fig. 2.)

[1] Allen and Clement, Amer. Jour. of Sci., Vol. 26, p. 101, 1908.

[2] Annals Astrophys. Obs., Vol. 1.

In Fig. 1 are given the transmission spectra of pure distilled water, held between two clear plates of fluorite. The thicknesses of the layers of water (accurately determined by placing different thicknesses of tinfoil between the plates) was as follows, viz: Curve $a = .014$ mm., curve $b = .038$ mm. and curve $c = .31$ mm. of water. For thinner layers see Carnegie Publication No. 65 and the PHYSICAL REVIEW. The important absorption bands occur at 1.48, 1.95, 3.0, 4.7 and 6.1 μ respectively.

SELENITE ($CaSO_4 + 2H_2O$).

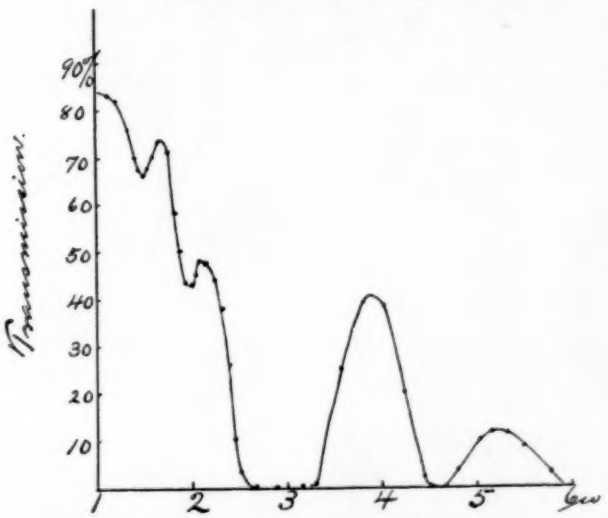

Fig. 2. Selenite. $t = .648$ mm.; water $= .318$ mm.

The transmission spectrum of a specimen of selenite 0.648 mm. in thickness, is given in Fig. 2. Since 21 per cent. of selenite is water, the thickness of the water if free would be 0.318 mm. (sp. gr. of selenite is 2.33). The specimen is transparent to 6 μ, while a layer of water 0.31 mm. is already opaque at 2.5 μ. The density of the water in selenite is so reduced that the absorption is only about one sixth to one tenth as great, see Fig. 1, curve *b*. For other thinner specimens see previous papers just quoted.

TREMOLITE, $CaMg(SiO_3)_4$.

The specimen of tremolite was quite transparent. The transmission of a section 0.23 mm. in thickness is given in curve *a*, Fig. 3. The equivalent layer of water would be 0.0138 mm. It is evident from this and from the transmission of a layer of water .014 mm. (Fig. 1), that the water in this mineral behaves like a

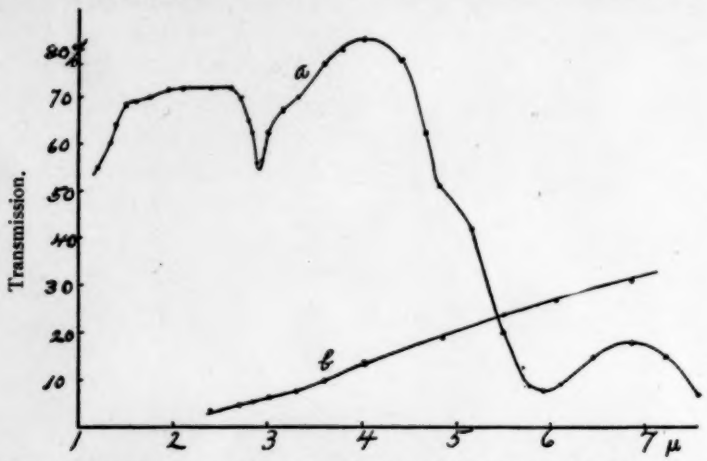

Fig. 3. Tremolite. $t = .23$ mm. Curve b, dehydrated specimen, $t = .015$ mm.

highly attenuated vapor. No absorption bands of water are visible, the small bands which are present being common to silicates. In curve *b* is shown the transmission of a dehydrated specimen of tremolite .015 mm. in thickness. It was an opaque white mass and the increase in transmission with wave-length is no doubt due to the decrease in the scattering of the incident energy.

MUSCOVITE MICA, $H_2KAl_3(SiO_4)_3$.

The transmission spectra are given in Fig. 4. Curve *a* was obtained with a rock salt prism, while curves *b* and *c* were observed with a fluorite prism. The thickness was .04 mm. Curve *b* shows the transmission of the specimen after dehydration. The absorption bands are common to silicates; and none are in common with those of water. The band of selective reflection beyond 9 μ does not seem to be affected by the constitutional water. The other bands disappear on dehydration, as they should, since on dehydration a new

compound is formed — or rather, as in this case, only the constituent oxides remain. The layer of mica is too thin to show the weak absorption band of silica at 2.9 μ.

In conclusion it may be added that in substances (whether solid solutions or crystals) containing 7 per cent. of water the water bands were easily detected spectroradiometrically. But when the water content falls as low as 2 to 3 per cent. of the total weight

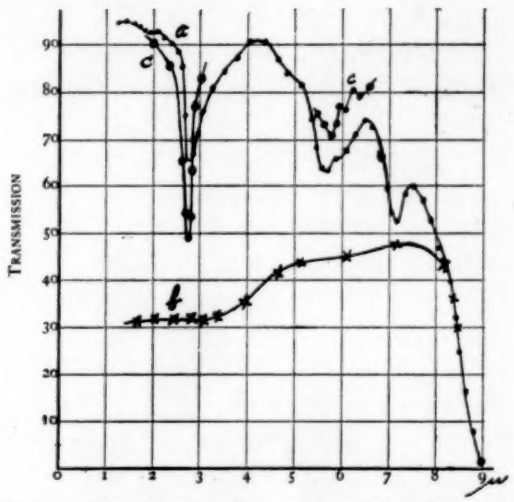

Fig. 4. Muscovite mica. Curve b, the same after dehydration; $t = .04$ mm.

of the substance, then the conditions which obtain in water vapor are found, and in the thin sections investigated the water bands are not detectable. The question then remains unexplained why a crystal containing water, and a solid solution of the same, show the absorption bands of water when other tests indicate that the crystal is a definite compound instead of discrete molecules of the substance cemented together with a definite amount of water.

WASHINGTON, D. C.,
August 21, 1909.

STUDIES IN LUMINESCENCE.

BY E. L. NICHOLS AND ERNEST MERRITT.

XI. THE DISTRIBUTION OF ENERGY IN FLUORESCENCE SPECTRA.[1]

THE energy of most continuous spectra is too feeble to permit of accurate measurements excepting in the infra-red and the longer wave-lengths of the visible spectrum, although we have a few determinations of the energy of the visible spectrum of the acetylene flame by G. W. Stewart[2] and by Coblentz that extend beyond the green. The direct measurement of the energy of even the brightest of fluorescence spectra, which are very small in intensity as compared with those of our ordinary artificial light sources, is therefore impracticable. We have shown however in previous papers of this series that it is possible to make quantitative spectrophotometric comparisons between fluorescence spectra and the spectrum of a standard such as the acetylene flame. If the distribution of energy of the source used for comparison be known, it is therefore easy to compute that of the fluorescence spectrum.

We have adopted this method in determining the energy distribution in the fluorescence spectra of fluorescein, eosin, and resorufin, with the results recorded below. The experimental work naturally falls under three heads: (1) The determination of the energy distribution in the standard source; (2) the spectrophotometric comparison of the fluorescence spectrum with the standard; (3) the measurement of the absorption of the fluorescent liquid, in order that the observed curve of fluorescence may be used to compute the typical curve.

Determination of the Distribution of Energy in the Spectrum of the Comparison Flame.

The comparison source used in the experiments to be described in this paper was an ordinary flat flame from an acetylene burner,

[1]A portion of the apparatus used in this investigation was purchased under a grant from the Carnegie Institution.

[2]G. W. Stewart, PHYS. REV., XVI., p. 123.

in front of which, at a distance of 1.4 cm., was mounted a metal screen having a circular hole 0.6 cm. in diameter, so as to cut off the light from all but the brighter central portions of the flame. This flame with its diaphragm was mounted in a metal box having a circular window opposite the diaphragm. The box was fastened to a base fitted to slide along a straight metal track. This track was mounted horizontally in the same vertical plane as the axis of one of the collimators of a Lummer-Brodhun spectrophotometer, and at such a height that the axis of the collimator extended would pass through the window in the box and through the center of the diaphragm to the flame itself.

In front of the slit of the collimator was mounted a sheet of clear white glass, the surface of which had been sufficiently roughened by grinding with powdered carborundum so that at whatever distance the flame might be placed the contrast field of the spectrophotometer would be of uniform brightness throughout. The loss of light by the interposition of the ground glass was found to be about 40 per cent. Its transmission throughout the range of wave-lengths used in our measurements was not measurably selective.

To determine the distribution of energy in the spectrum of the light received from the comparison flame after passing through the ground glass and the optical parts of the spectrophotometer, this spectrum was carefully compared wave-length by wave-length with the light received through the other collimator of the instrument from a black body of known temperature.

Fig. 78.

The black body, Fig. 78, consisted of a tube of Acheson graphite about 50 cm. long, of 1.7 cm. bore and 4.0 cm. external diameter. In the middle this tube was turned down for about 20 cm. until the thickness of the walls was reduced to about 0.4 cm. and the thin-walled cylindrical chamber thus formed was heated by means of an alternating electric current furnished by a step-down transformer, of whose secondary circuit it formed the principal part.

The ends of the cylindrical body were graphite plugs, each with

an axial hole one cm. in diameter. Through one of these passed a tube of fused quartz containing a platinum-rhodium-platinum thermo-junction of wires which had been calibrated at the Bureau of Standards. This junction received radiation from the surrounding walls and could be pushed in and out at will so as to ascertain the range of temperatures within the black body. Through the opening in the other plug and through corresponding openings in diaphragms located nearer the ends of the graphite tube, light from the incandescent top of the quartz tube reached the spectrophotometer.

To reduce heat losses and prevent the too rapid oxidation of the graphite, the tube was embedded to a depth of about 8 cm. in a mass of powdered magnesite, which was contained in a hollow cylinder of magnesium oxide and asbestos such as is used for the packing of large steam pipes.

When the primary circuit was supplied with 80 amperes at 110 volts the temperature of this improvised furnace, as indicated by the

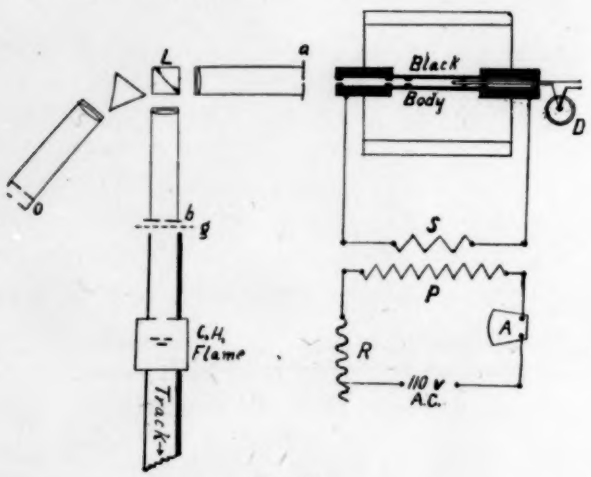

Fig. 79.

thermo-junction, rose slowly to nearly 1500° C. at which temperature it remained with little change for a considerable time. Temperatures were determined in the usual way by means of a potentiometer and cadmium cell.

The arrangement of the apparatus is shown in Fig. 79, in which R is an adjustable resistance, A is an a.c. ammeter, P is the primary

coil of transformer, S is the secondary coil, D is a Dewar flask with the cold junction in ice, a and b are the collimator slits of the spectrophotometer, L is the Lummer-Brodhun prism of the spectrophotometer, O is the observing telescope of the spectrophotometer, g is the ground glass in front of slit b.

The slits a and b were set once for all to convenient widths, b being 30 divisions = 0.6 mm. in width, and a 0.06 mm. The adjustable diaphragm in O was of the same width as slit b.

In this determination one observer made settings for wave-length and watched the contrast fields of the spectrophotometer, while another recorded the positions of the comparison flame when, for each region of the spectrum, equality had been reached. In the meantime a third observer followed the changes of temperature with the potentiometer and reported the E.M.F. of the thermo-junction for each setting of the spectrophotometer. Readings were begun when a temperature of 1410° (absolute) was reached. Subsequently the current was slightly reduced and further sets of readings were made throughout the spectrum.

From these data the distribution of energy in the spectrum of the comparison flame was computed.

Wien's equation

$$I = C_1 \lambda^{-5} e^{-\frac{C_2}{\lambda T}}$$

was taken as giving the energy in the region of the spectrum at which measurements were made. The accepted value, for an ideal black body, of the constant C_2 (*i. e.*, C_2, = 14,500) was assumed to be applicable to the present case, and the quantity $C_2/\lambda T$ was calculated from the readings of wave-length and temperature. Since relative values only were desired, the constant C_1 was given a value convenient for purposes of computation.

The two slits of the spectrophotometer were maintained at a constant width throughout, and the distance (d) of the comparison flame was varied until the intensities of the spectra were equal The energy of any given region of wave-length λ was therefore proportional to the ratio $I_\lambda/(1/d^2)$, where I_λ was the energy of the corresponding region of spectrum of the light from the black body, computed as above.

Observations were made for twelve regions lying between .477 μ and .656 μ, and in the course of the determination the spectrum was traversed four times. Good agreement existed between the various readings in each region with the exception of the observations immediately following changes made in the resistance of the

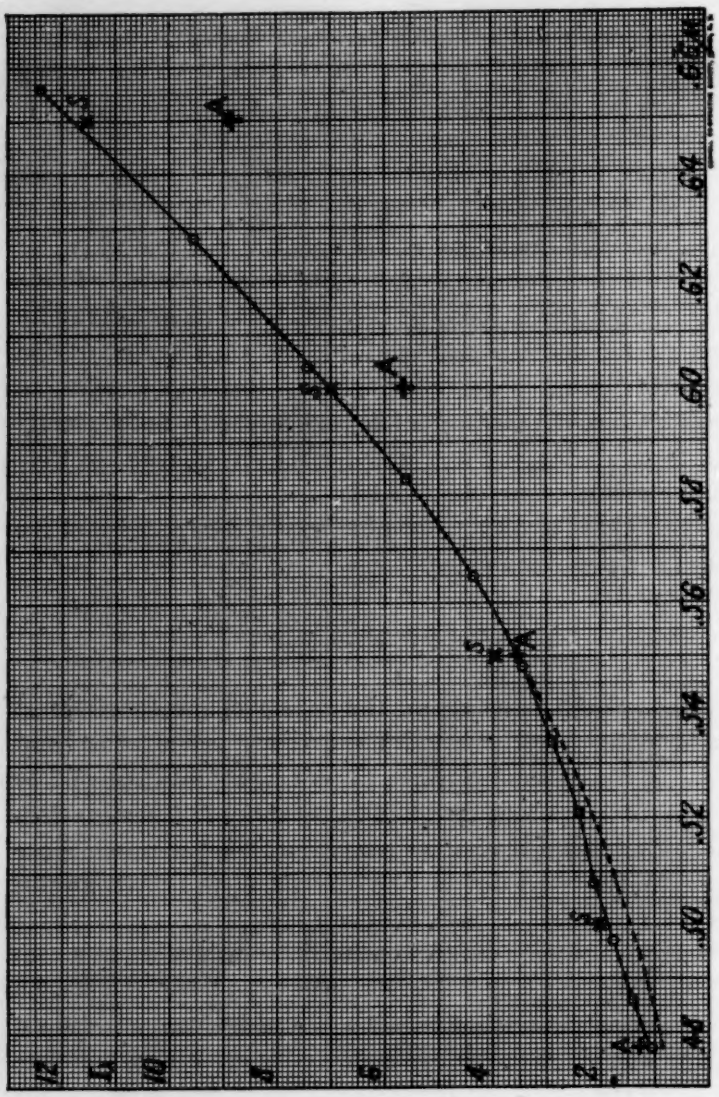

Fig. 80. Distribution of energy in the spectrum of the acetylene flame. The points marked *S* correspond to Stewarts' direct measurements with the radiometer. The points marked *A* are derived from Ångstrom's measurements of the Hefner Lamp. The dotted line is computed from Wien's equation.

primary circuit. These were rejected and all other readings were used in the computations and averaged for each wave-length separately. The results are given in Table I. and are shown graphically in Fig. 80.

TABLE I.

Wave-length.	$I_\lambda/(1/d^2)$	Wave-length.	$I_\lambda/(1/d^2)$
.656	248.0	.534	58.70
.628	189.0	.521	48.50
.604	149.2	.508	42.50
.583	112.9	.497	37.73
.565	87.0	.486	29.33
.548	69.2	.477	21.25

Wien's equation has been employed, although in quite a different way, by Knut Ångström [1] for the determination of the distribution of energy in the spectrum of the flame of the Hefner lamp and it is of considerable interest to compare his determination, which involved neither the direct measurement of temperatures nor observations upon a black body, with the results of the experiment just described.

TABLE II.

Spectrophotometric comparison of the acetylene comparison flame viewed through the circular diaphragm and ground glass, with flame of a Hefner standard lamp.

λ	C_2H_2/Hefner.	λ	C_2H_2/Hefner.
.656 μ	.916	.534 μ	1.32
.628	.950	.521	1.43
.604	.990	.508	1.53
.590	1.00	.495	1.69
.583	1.04	.487	1.83
.565	1.11, 1.15	.477	1.90
.548	1.25		

For this purpose we made a careful spectrophotometric comparison between our acetylene standard and a Hefner flame (see Table II. and Fig. 81). From Ångström's curve of the distribution of energy in the spectrum of the Hefner standard we then computed the relative intensities of our comparison flame for several regions lying between .656 μ and .483 μ. The points so determined are shown in Fig. 80 by crosses marked "A."

[1] Ångström, Nova Acta Upsaliensis, III., Vol. XXII., 1904.

Several points determined by Stewart by direct measurement with the radiometer are also shown in Fig. 80, being marked "S."

It is a matter of some interest to determine to what extent the visible radiation from the acetylene flame corresponds to the visible radiation from a black body. We find that the curve computed from Wien's equation is practically identical with our experimental

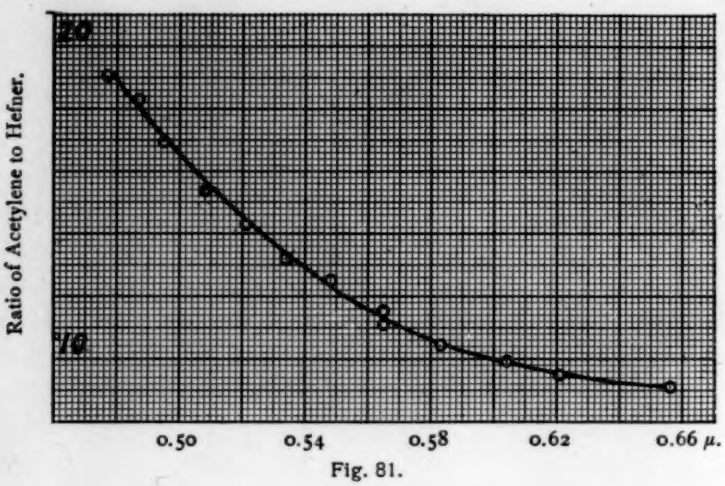

Fig. 81.

curve from 0.56 μ to 0.65 μ. But for wave-lengths less than 0.56 μ the curve based upon Wien's equation (shown by the broken line in Fig. 80) deviates considerably from that determined by experiment. The acetylene flame appears to possess a band of abnormally high radiating power in the region lying between .55 μ and the violet end of the spectrum.

Comparison of the Fluorescence Spectra with the Spectrum of the Standard Acetylene Flame.

Before making the final spectrophotometric determinations from which the distribution of energy in the spectrum of various fluorescence spectra were to be computed, a careful study was made of the effect of slit-width upon the form of the observed curves.

In the ordinary use of the Lummer-Brodhun spectrophotometer slit *a* (Fig. 79) would be of constant width and slit *b* would be varied. The accuracy of the screw of the latter was therefore tested by

mounting the slit, which had been removed from the instrument, in the field of a projecting lantern and measuring the width of the slit-image, focused upon a horizontal millimeter scale at a distance of about eight meters. Variations from constancy of the ratio of widths to micrometer readings were found negligible for a range of two turns of the screw. Studies of the brightness of the spectrum obtained when this slit was used showed, however, marked deviations from the expected proportionality between slit-width and intensity, especially for widths of less than .01 cm.

It was therefore decided to avoid changes in slit width by using the method of comparison used in determining the distribution of energy in the spectrum of the comparison flame.

In this method the two slits of the spectrophotometer remain unchanged in width, and equality of brightness is obtained for each region of the spectrum by moving the comparison flame along a bar or track parallel to the axis of the collimator. With the system of screens which we employed to exclude stray light, the law of inverse squares was found to hold for the entire range of distances used in our experiments.

The three substances selected for measurement were fluorescein in aqueous solution slightly alkaline, eosine in alcohol, and resorufin in alcohol.

The solutions in each case were as dilute as was found practicable so as to reduce the correction for absorption to a minimum.

In the determination of the fluorescence curves the solution was placed in rectangular cell of white glass (*f*, Fig. 82) and was ex-

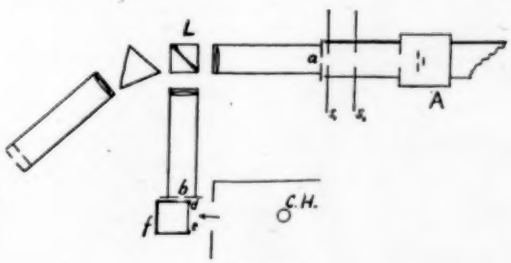

Fig. 82.

cited by the light from a Cooper-Hewitt mercury lamp, *C. H.* The tube of this lamp was vertical and mounted at a distance of about

30 cm. from the wall of the cell. Only those portions of the tube were used which were nearly in the same horizontal plane as the cell. The beam of exciting light entered the cell, *f*, Fig. 82, in the direction of the arrow at right angles to the axis of the collimator.

The cell was enclosed within a metal box with black, matte, oxidized surfaces, and having only the broad rectangular opening *de* for the admission of the exciting light and a narrow, vertical slit-like aperture opposite the slit *b* through which the fluorescence was viewed.

The selection of the mercury arc, with its almost complete absence of light in the region occupied by the fluorescence bands to be measured, afforded further protection against stray light. In the study of the fluorescein solution the additional precaution was taken of inserting a cell of ammonio-sulphate of copper in water between the lamp and the fluorescent liquid, thus cutting off the yellow and green lines of the arc almost completely. The mercury lamp was fed from a storage battery of 120 volts with suitable resistance in series, and under these conditions it furnished an exciting light of unexpected constancy — surpassing in this respect any other source of suitable character and sufficient intensity with which we have had experience.

The arrangement of the apparatus for determining the fluorescence spectra is shown in Fig. 82. The plan is similar to that used in comparing the acetylene flame with the black body. But the photometer track carrying the flame was mounted in line with collimator *a*, while the fluorescence cell was placed in front of slit *b*. In the figure, *A* is the comparison flame; s_1 and s_2 are screens to prevent stray light from entering slit *a*; *f* is the cell of fluorescent liquid, and *C. H.* is the Cooper-Hewitt mercury arc lamp.

The procedure was as follows:

Slits *a* and *b* were set at equal widths of 50 divisions = .05 cm. The comparison flame was then moved up to a point on the track just in front of the aperture in screen s_2. The observing telescope was set for that region of the spectrum corresponding with the maximum of the fluorescence band to be measured. The fluorescent solution in cell *f* was diluted until its spectrum for that region

was slightly stronger than the corresponding region in the spectrum of the comparison flame. By slightly shifting the observing telescope in either direction two places could now be found, lying a

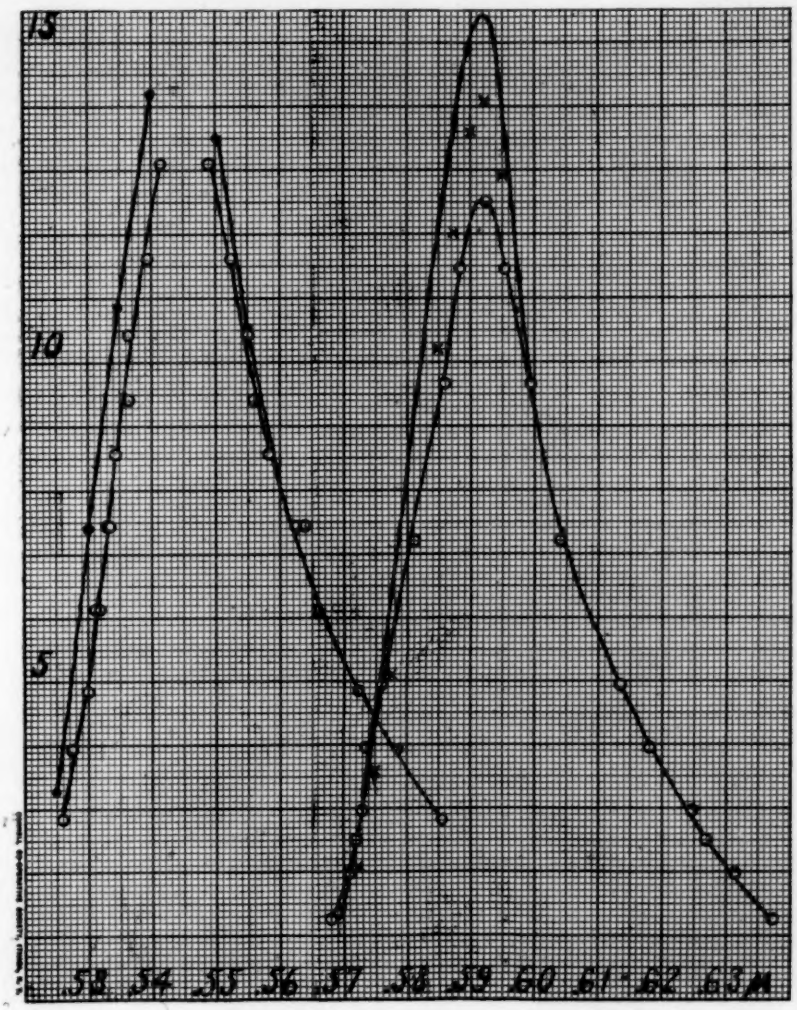

Fig. 83. Eosin (to the left) and Resorufin. The observed points are marked by circles.

short distance from the crest of the fluorescence band, at which the two spectra were of equal brightness. The circle readings of these positions were noted, and the position of the comparison flame was

read upon the scale of the photometer track. The flame was then moved to a slightly greater distance from slit *a*, and two new positions were formed for the observing telescope, corresponding to

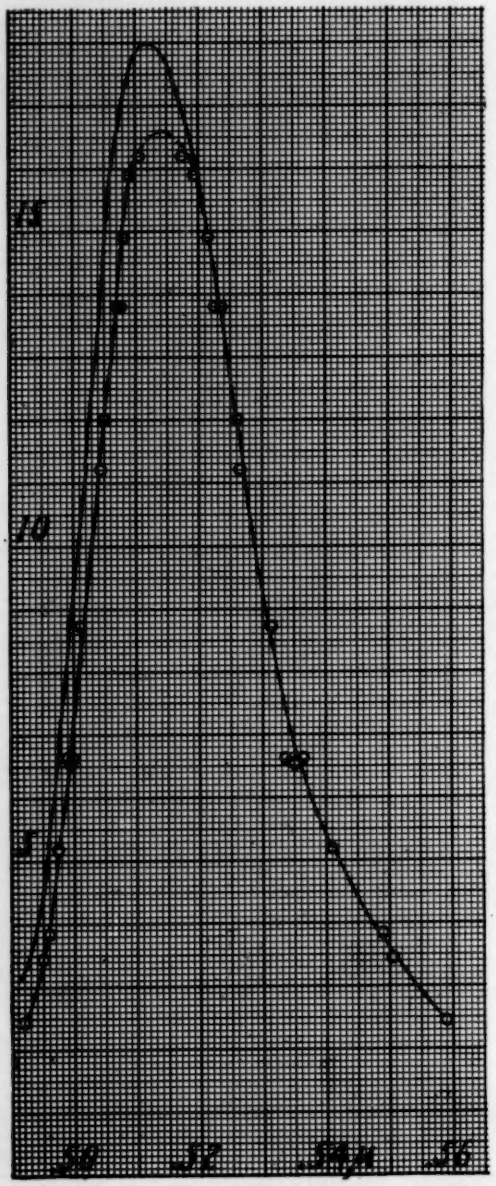

Fig. 84. Fluorescein. The observed points are marked by circles.

points of equal brightness of the band further from the crest. In this way the entire band was explored several times, and from these sets of readings the intensity of the band at various wave-lengths was computed in terms of the corresponding intensities of the spectrum of the acetylene flame.

From these values the observed curves in Figs. 83 and 84 were plotted. The observed points are indicated by circles. In the case of eosin the wave-length of the crest is nearly the same as that of the green mercury line. Measurements in the region of the crest were therefore rendered uncertain by the presence of stray light from the green line. For this reason all the measurements in this region have been discarded. Observations near the crest of the fluorescein curve were also somewhat discordant, so that we do not regard this part of the curve as determined with much accuracy.

To obtain from the observed curves the distribution of energy in the fluorescence spectra it was necessary to make corrections for slit-width and absorption, and to multiply the ordinates of each corrected curve by the ordinates of the same wave-length in the curve giving the distribution of energy in the spectrum of the acetylene flame.

The Correction for Slit-width.

In the spectrophotometric comparison of sources of light having continuous spectra and nearly the same luminosity curves the correction for slit-width disappears; but in the case of spectra consisting of narrow bands this is far from being the case. The slit-width correction used in the determination of the energy curves of incandescent solids does not apply, partly because it is the luminosity of the rays rather than their energy that is important, and partly because the distribution of luminosity in *two* sources has to be considered. The slit correction applicable to the Lummer-Brodhun spectrophotometer may be derived as follows: Let the luminosity curve of the source S_1, in front of the slit A, have the equation

$$L_1 = f(\lambda)$$

when the distance of the source is such as to give the standard intensity, which we shall call unity. If the distance is varied so that the intensity becomes i, then

$$L_1 = if(\lambda),$$

λ being the wave-length.

The luminosity of the source S_2 in front of the slit B will then be given by the equation

$$L_2 = rf(\lambda),$$

where r is the ratio of the energy of S_2 at the wave-length λ to the energy of S_1 at the same wave-length. r is itself a function of λ unless two sources are identical in quality.

Images of the slit A are found in the focal plane of the telescope for each wave-length of the spectrum of S_1. If the spectrum is continuous, we therefore have a series of overlapping images, forming a spectrum of greater or less impurity according to the width of the slit A.

The light reaching the eye from the slit A will depend upon the width of A, being proportional to this width if other conditions remain constant. But it will also depend upon the width of the aperture, C, at the principal focus of the telescope, through which aperture the light used in making settings must pass. If the spectrophotometer is used without an eye-piece, so as to obtain the benefit of the contrast field formed by the Lummer-Brodhun cube, all the light passing through C is used in illuminating the field, and the color is that resulting from mixing all the wave-lengths present. When the instrument is set to a match we therefore have equality between the total luminosity of the rays passing through C from A, and the total luminosity of the rays passing through C from B.

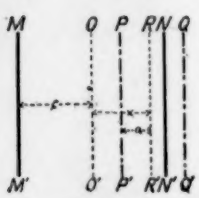

Fig. 85.

An expression for the total luminosity of the rays from A may be found as follows:

Let MN be the aperture at the focus of the telescope. It will be convenient to express the width $2c$ of this aperture in terms of wave-length. $2c$ is therefore not a constant, even if the actual width of the aperture is invariable, but depends upon the dispersion in the region of the spectrum where the observations are made. The widths of the slits A and B, denoted by $2a$ and $2b$ respectively, will also be expressed in terms of wave-length. We shall consider first the case were $a < c$.

Let the center of C (OO' in the diagram) correspond to the wave-length λ. That image of the slit A which is formed by light of

wave-length λ will have its center coincident with the center of the aperture. The image formed by light of wave-length $\lambda + x$ will be displaced by the distance x, so that its central line falls at RR'. For values of x lying between $+(c-a)$ and $-(c-a)$ all of the light forming the image of a will pass through the aperture. The total luminosity reaching the eye from such images will therefore be

$$L_1 = \frac{2am}{d_1^2}\int_{-(c-a)}^{+(c-a)} f(\lambda + x)dx = \frac{2am}{d_1^2}\int_0^{c-a}\{f(\lambda + x) + f(\lambda - x)\}dx,$$

where d_1 is the distance of the source S_1 from the slit. m is a factor, depending upon the dispersion of the prism, such that ma is proportional to the width of the slit in scale divisions. It is clear that $2am/d^2$ measures the intensity of the light entering the slit, the intensity being unity when the source is at unit distance and the slit width one division.

For values of x lying between $c-a$ and $c+a$ only a part of the image will be transmitted, the transmitted fraction being

$$1 - \frac{x + a - c}{2a}.$$

The total transmitted luminosity from these images that are partially transmitted will therefore be

$$\frac{2am}{d^2}\int_{c-a}^{c+a}\left(1 - \frac{x+a-c}{2a}\right)\{f(\lambda + x) + f(\lambda - x)\}dx$$

$$= \frac{2am}{d^2}\int\left\{\frac{a+c}{2a} - \frac{x}{2a}\right\}\{f(\lambda + x) + f(\lambda - x)\}dx.$$

Upon expanding $f(\lambda + x)$ and $f(\lambda - x)$ we have

$$f(\lambda + x) + f(\lambda - x) = f(\lambda) + xf'(\lambda) + \frac{x^2 f''}{2}(\lambda) + \cdots$$

$$+ f(\lambda) - xf'(\lambda) + \frac{x^2 f''}{2}(\lambda) - \cdots$$

$$= 2f(\lambda) + x^2 f''(\lambda) + \cdots.$$

For any ordinary case the terms in higher powers of x may be neglected.

The two integrals therefore become

$$\int_0^{c-a}\{f(\lambda+x)+f(\lambda-x)\}dx=\int_0^{c-a}[2f(\lambda)+x^2f''(\lambda)]dx$$

$$=2(c-a)f+\frac{(c-a)^3}{3}f''$$

and

$$\int_{c-a}^{c+a}\left[\frac{c+a}{2a}-\frac{x}{2a}\right][2f+x^2f'']dx=\frac{c+a}{2a}\left[4af+\frac{(c+a)^3-(c-a)^3}{3}f''\right.$$

$$\left.-\frac{1}{2a}\left[\{(c+a)^2-(c-a)^2\}f+\frac{(c+a)^4-(c-a)^4}{4}f''\right]\right.,$$

where f and f'' are written for $f(\lambda)$ and $f''(\lambda)$ respectively.

Upon adding the two integrals and introducing the factor am/d_1^2 we have

$$L_1=\frac{2ma}{d_1^2}\left[2cf+\frac{a(\overline{c-a}^2+2c^2)}{3}f''\right].$$

In case $a>c$ the corresponding expression is found to be

$$L_1=\frac{2ma}{d_1^2}\left[2cf+\frac{c(a^2+c^2)}{3}f''\right].$$

In any case therefore we have

$$L_1=\frac{2ma}{d_1^2}(2cf+k_1f'')$$

where k_1 takes the value $c(c^2+a^2)/3$ when $a>c$, $a(\overline{c-a}^2+2c^2)/3$ when $a<c$, and $2a^3/3$ when $c=a$.

Similarly for that portion of the field which is illuminated by S_2

$$L_2=\frac{2mb}{d_2^2}\left[2crf+k_2\left(\frac{\partial}{\partial\lambda}\right)^2(rf)\right].$$

When the two fields are set to equality we have therefore

$$\frac{2ma}{d_1}\left[2cf+k_1f''\right]=\frac{2mb}{d_2^2}\left[2crf+k_2\frac{\partial^2(rf)}{\partial\lambda^2}\right].$$

Expanding $\partial^2(rf)/\partial\lambda^2$ and remembering that the second term in the

bracket is in each case small we have:

$$\frac{d_2^2}{d_1^2}\frac{a}{b}\left[1+\frac{k_1 f''}{2cf}\right]=r\left[1+\frac{k_2}{2crf}(r''f+2r'f'+rf'')\right],$$

$$r=\frac{d_1^2}{d_2^2}\frac{a}{b}\left[1+\frac{k_1-k_2}{2c}\frac{f''}{f}-\frac{k_2}{c}\frac{r'f'}{rf}-\frac{k_2}{2c}\frac{r''}{r}\right].$$

An approximate value of r, usually a close approximation, is obtained by neglecting all terms after the first. This approximate value having been plotted as a function of λ, r' and r'' may be determined; and since f' and f'' may be obtained from the luminosity curve of the source A, the correction terms in the above expression can readily be computed.

In the experiments described in this paper the conditions were so chosen as to make $a=b=c$. In this case the expression for r becomes

$$r=\frac{d_1^2}{d_2^2}\left[1-\frac{a^2}{3}\cdot\frac{r''}{r}-\frac{2a^2}{3}\frac{r'}{r}\frac{f'}{f}\right].$$

If Δr is the increase in r which results from changing the wavelength from λ to $\lambda+2a$, and if Δf is the corresponding increase in f, we have approximately:

$$r'=\Delta r/2a, \quad f'=\Delta f/2a.$$

For purposes of graphical computation we may conveniently express the approximate value of r'' in terms of the distance DC, Fig. 86. If this distance be called δr it may be readily shown that $r''=2\delta/a^2$,

$$\therefore r=\frac{d_1^2}{d_2^2}\left[1-\frac{2}{3}\frac{\delta r}{r}-\frac{1}{6}\frac{\Delta r}{r}\frac{\Delta f}{f}\right].$$

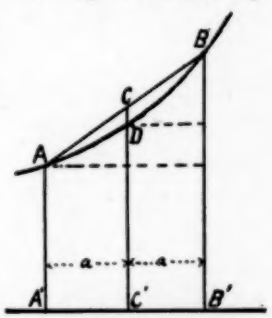

Fig. 86.

In computing these correction terms the luminosity curve given by Tufts was used.[1] The values of Δr and δr were taken from the curve showing the relation between λ and the approximate value of r.

[1] Tufts' curve was obtained for an incandescent light. But the difference between the color of the acetylene flame and that of the glow lamp in the region considered is so small that the error introduced is quite inappreciable.

The correction depending upon δr is important only when the curvature of the r curve is considerable. In the present instance this correction is large for regions near the crest of the curve, but insignificant elsewhere. The importance of the correction is well shown in the curves for resorufin (Fig. 83) where the points marked with crosses show the curve after the slit correction has been applied. In the case of eosin and fluorescein the region near the crest was uncertain for the reasons already mentioned (f), so that the slit correction has not been applied in this region.

The second correction term, depending upon the product $\Delta r \Delta f$, is negligible near the crest of the luminosity curve of the source, where Δf is small. The term is thus of no significance in the case of eosin and fluorescein. Even with resorufin, where the whole luminescence spectrum lies well to infra side of the crest of the luminosity curve, this correction is important only on the steep side of the curve. The result of applying the correction is shown by the points marked with crosses.

The Correction for Absorption.

The fluorescent light which enters the slit of the spectrophotometer in the foregoing experiments comes from a layer of liquid in the fluorescence cell having a thickness determined by the opening de, Fig. 82, through which the exciting light enters the cell. This layer, which is to be considered as uniformly fluorescent, extends from $x = x_1$ to $x = x_2$, where x is the distance from any point from which fluorescent light emanates to the wall of the cell in the direction towards the slit of the spectrophotometer.

Let the intensity of light, of any wave-length λ, sent towards the slit from unit layer be i, and from a layer of thickness dx, be idx. If the coefficient of absorption of the liquid be α the light reaching the slit from layer dx is $idxe^{-\alpha x}$ and the total intensity of light reaching the slit from the whole of the excited layer is

$$I = i\int_{x_1}^{x_2} e^{-\alpha x}dx$$

$$= \frac{i}{\alpha}\left[e^{-\alpha x_1} - e^{-\alpha x_2}\right].$$

In the cell used in these determinations x_2 was 36.5 mm. and x_1 was 2.5 mm.

The coefficient α was determined by measuring the transmission of a cell containing a sufficient thickness of the fluorescent liquid to reduce the intensity of light of the wave-length of the middle

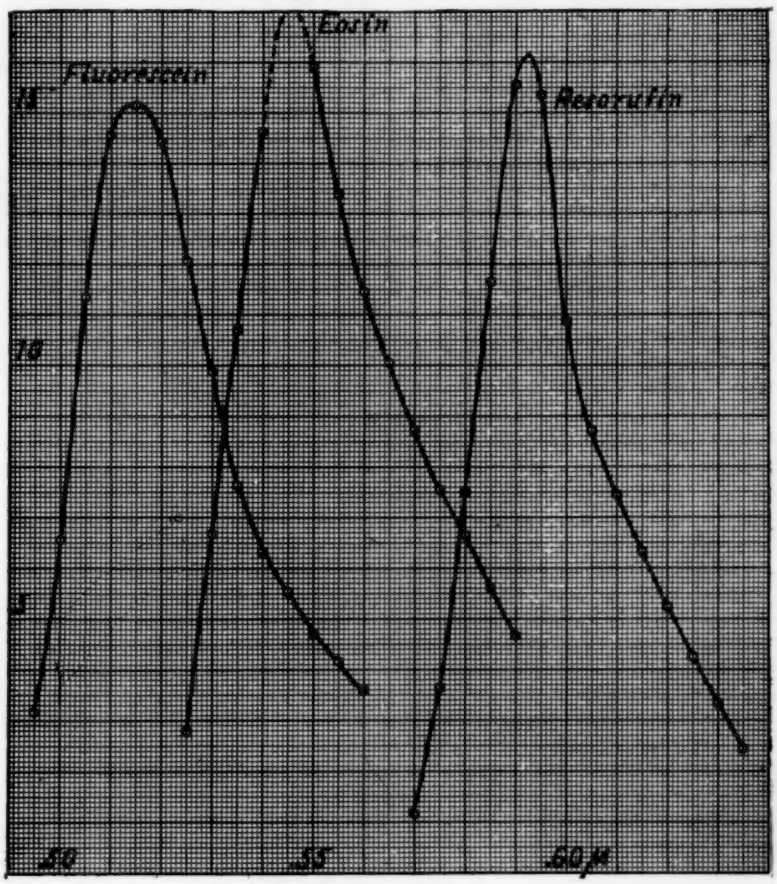

Fig. 87.

of the absorption band to about 40 per cent. The correction for the losses of light in the glass and the solvent was determined by measuring transmission through the same cell when filled with absolute alcohol (or in the case of fluorescein with water).

The correction for absorption, like that for slit-width, is of importance only in certain regions. The form of the fluorescence curves after the application of both corrections is shown in Figs. 83 and 84.

The Energy Curves of Fluorescence.

From the data corrected in the manner indicated in the two preceding sections curves for the distribution of energy in the fluorescence spectrum of the three substances under investigation were derived by multiplying various ordinates of the corrected curves of Figs. 83 and 84 by the ordinate of same wave-length in the energy curve of the acetylene standard (Fig. 80).

The resulting curves are given in Fig. 87. They suggest by their form a close resemblance between black body radiation and fluorescence, excepting that the range of wave-lengths in the latter case is much smaller. Attempts to find some simply modified form of Wien's equation which will represent the results have thus far been unsuccessful.

Physics Laboratory of Cornell University,
April, 1909.

ON THE PROBABILITY OF AN INHERENT RELATION OF THE ELECTRICAL RESISTANCE AND THE HARDNESS OF STEEL.

By Carl Barus.

1. *Introduction.* — Some time ago[1] Professor Strouhal and the writer brought forward a relation between the thermo-electric power and the specific resistance of steel varying with temper from hard to soft. More than 90 states of temper were examined, the rods being of the same kind of Stubb's steel throughout, tempered, etc., with scrupulous care. This relation, as shown in the annexed figure (*a* thermoelectric power in micro-volts relatively to pure silver, *s* specific resistance in microhms per c.c., at 0° C.), was remarkable in the first place for the enormous interval between the extreme values of the variables (change of electrical resistance being over three fold from soft to hard, for instance) and in the second place, from the fact that the coördinates in question determine a straight line. This is not true (*l. c.*) for other alloys. Moreover for the case of such large variations as those in question for steel, one can hardly speak of an initial tangent.

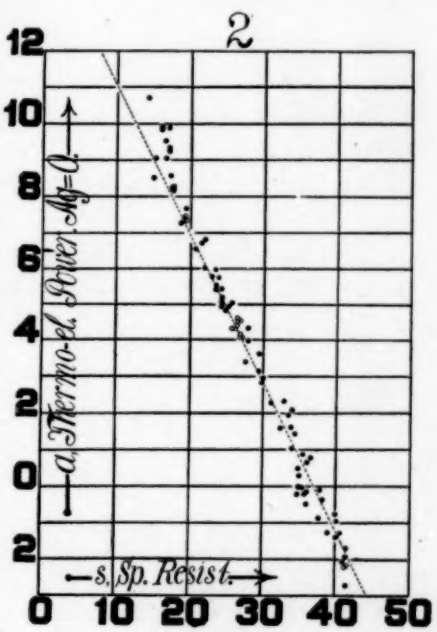

Fig. 1.

[1] Wied. Annalen, VII., 1879, p. 383; XI., 1880, p. 930. Also Bulletin No. 14, U. S. Geological Survey, 1885, chapter 2.

The constants of the line for steel were found to be, if

$$a = m + ns,$$

$$m = 15.176, \quad n = -.4123,$$

all data being expressed in c.g.s. units and referred to pure silver and 0° C. Hence $m - a$, which we called thermo-electric hardness, is proportional to s and is virtually referred to a standard steel rod whose specific resistance is zero. This eliminates the silver.

2. *Case of Two Phases.* — The two functions, a and s, of the temper of steel between the glass hard and soft states, however sensitive for discrimination, have thus far been regarded as a mere index to that quality. It does not seem improbable that they are more than this, if we regard tempered steel as a mixture of hard and soft molecules, sufficiently intimate to give but little variation of the elastic constants, while the metal passes from hard to soft. I have already made such a supposition in an earlier paper[1] with advantage.

In such a case, let q be the number of hard molecules and $1 - q$ the number of soft molecules per sq. cm. of any interface within the metal. The passage from hard to soft is thus a change of q from 1 to 0. Hence for conduction normal to the interface we may write

$$\frac{1}{s} = \frac{q}{s_1} + \frac{1 - q}{s_2}, \tag{1}$$

and

$$\frac{a}{s} = q\frac{a_1}{s_1} + (1 - q)\frac{a_2}{s_2}, \tag{2}$$

where a_1, s_1 denote the thermo-electric power and electrical resistance of extremely hard steel, a_2, s_2 the same variables for extremely soft steel, while a, s, refer to any intermediate states of temper. Hence if equations (1) and (2) are to be compatible

$$a = \frac{a_2 s_1 - a_1 s_2}{s_1 - s_2} + \frac{a_1 - a_2}{s_1 - s_2} s. \tag{3}$$

In other words, the relation of a and s is inherently linear as it was actually found to be for steel, but not generally for alloys.

[1] PHYS. REV., Vol. XXIX., 1909, pp. 516–524. The substance of this and of the above paper were given at Clark University, September 8.

3. *Case of More than Two Phases.* — It is clear moreover that the linear relation will in general cease to hold, if there are more than two kinds of molecules present. In case of three groups for instance

$$\frac{1}{s} = \frac{q_1}{s_1} + \frac{q_2}{s_2} + \frac{1 - q_1 - q_2}{s_3}, \tag{4}$$

$$\frac{a}{s} = q_1 \frac{a_1}{s_1} + q_2 \frac{a_2}{s_2} + (1 - q_1 - q_2) \frac{a_3}{s_3}, \tag{5}$$

whence

$$a = \frac{a_2 s_3 - a_3 s_2}{s_3 - s_2} + \left(\frac{a_3 - a_2}{s_3 - s_2} + \frac{q_1}{s_1} \frac{s_3(a_1 - a_2) + s_1(a_2 - a_3) + s_2(a_3 - a_1)}{s_3 - s_1} \right) s, \tag{6}$$

which reduces to the preceding equation (3) when $q_2 = 0$. In general, however, since q is essentially variable with s, it follows that a is no longer linear with respect to s. This is the probable case for alloys. To use equation (6), however, some relation between the three groups of molecules present in the ratio of $q_1 : q_2 : 1 - q_1 - q_2$ would have to be supplied, and it would be interesting to endeavor to derive this from investigations with alloys. If there are more phases than three the case would be correspondingly involved.

4. *Conclusion.* — It appears therefore probable that the electrical resistance or the thermo-electric hardness of steel, is more than a mere empiric expression of its state of temper. We may write for r the ratio of the number of hard to the number of soft molecules per c.c. of tempered steel

$$r = \frac{q}{1 - q} = \frac{1/s_2 - 1/s}{1/s - 1/s_1} = \frac{\lambda_2 - \lambda}{\lambda - \lambda_1},$$

i. e., the position which the electrical conduction λ takes between the conductions λ_2 and λ_1 of extremely soft and extremely hard steel.

From this point of view, moreover, the phenomenon of temper as exhibited in the preceding paper (*l. c.*) becomes an admirable test of a law adequately broad to express dissociation in solid media, subject to time and temperature.

BROWN UNIVERSITY,
PROVIDENCE, R. I.

ON THE THERMODYNAMICS OF BLACK RADIATION.

BY PAUL SAUREL.

IN a recent memoir,[1] Planck has obtained formulas which express the energy, the entropy, the electromagnetic momentum and the pressure of a moving hollow space, which is the seat of black radiation, in terms of its volume, temperature and velocity. Two distinct demonstrations are given by Planck. The first consists in combining with the general principles of thermodynamics some formulas that are due to Mosengeil, while the second is an illustration of the fruitfulness of the principle of relativity. In view of the interest which attaches to these formulas it may not be out of place to indicate how simply they can be obtained by combining the general principles of thermodynamics with a single result of electromagnetic theory.

Before considering a moving hollow space let us first consider a hollow space which is at rest, and let us denote the energy, the entropy, the volume, the temperature and the pressure of the black radiation which fills this space by ε, η, v, t, p respectively. Then if the general principles of thermodynamics apply to this system, we may write the well known equation

$$d\varepsilon = td\eta - pdv. \tag{1}$$

But we can go further than this and write

$$\varepsilon = t\eta - pv. \tag{2}$$

To justify this equation we observe that the energy must be a homogeneous function of the first degree of the entropy and the volume and that consequently

$$\varepsilon = \eta \frac{\partial \varepsilon}{\partial \eta} + v \frac{\partial \varepsilon}{\partial v}. \tag{3}$$

[1] M. Planck, Zur Dynamik bewegter Systeme, Berliner Berichte, p. 542, 1907; Ann. d. Phys., vol. 26, p. 1, 1908.

If we now make use of the fact that the partial derivatives which appear in this last equation are by equation 1 respectively equal to t and $-p$ we get at once equation 2.

By differentiating equation 2 and by making use of equation 1, we get

$$0 = \eta dt - v dp, \tag{4}$$

and from this it is easy to show that p is a function of t. Thus we may write

$$p = f(t). \tag{5}$$

Moreover, from equations 4 and 5 we get

$$\frac{\eta}{v} = \frac{dp}{dt} = f'(t), \tag{6}$$

and finally from equations 2, 5 and 6 it follows that

$$\frac{\varepsilon}{v} = tf'(t) - f(t). \tag{7}$$

Thus far we have used only the general thermodynamic principles. Let us now introduce into our reasoning one result of electromagnetic theory, namely, the fact that the radiation pressure is equal to one third of the specific energy:

$$p = \frac{1}{3}\frac{\varepsilon}{v}. \tag{8}$$

From equations 5, 7 and 8 we get

$$tf'(t) - f(t) = 3f(t), \tag{9}$$

or

$$\frac{f'(t)}{f(t)} = \frac{4}{t}, \tag{10}$$

or finally

$$f(t) = \frac{a}{3}t^4, \tag{11}$$

where a is a constant. If we insert this value of $f(t)$ in equations 5, 6, 7 we get at once the classic formulas for a system at rest

$$p = \frac{a}{3}t^4, \tag{12}$$

$$\eta = \frac{4a}{3} t^3 v, \tag{13}$$

$$\varepsilon = at^4 v. \tag{14}$$

Let us now consider a hollow space moving with the velocity q and let g denote its electromagnetic momentum. Our thermodynamic equation 1 no longer applies; as Planck has shown we must complete it by adding a term qdg corresponding to the work done in adding momentum to the system. Accordingly we write

$$d\varepsilon = td\eta - pdv + qdg. \tag{15}$$

As before we can go further and write

$$\varepsilon = t\eta - pv + qg. \tag{16}$$

For since the energy must be a homogeneous function of the first degree of the entropy, volume and momentum, we may write

$$\varepsilon = \eta \frac{\partial \varepsilon}{\partial \eta} + v \frac{\partial \varepsilon}{\partial v} + g \frac{\partial \varepsilon}{\partial g}. \tag{17}$$

If we notice that the partial derivatives in this equation are, in virtue of equation 15, respectively equal to t, $-p$ and q we get at once equation 16.

By differentiating equation 16 and by making use of equation 15 we get

$$0 = \eta dt - vdp + gdq, \tag{18}$$

and from this it is easy to show that p is a function of t and q. Thus we may write

$$p = f(t, q). \tag{19}$$

Moreover, if we write equation 18 in the form

$$dp = \frac{\eta}{v} dt + \frac{g}{v} dq, \tag{20}$$

it follows that

$$\frac{\eta}{v} = \frac{\partial p}{\partial t} = \frac{\partial f}{\partial t}, \tag{21}$$

$$\frac{g}{v} = \frac{\partial p}{\partial q} = \frac{\partial f}{\partial q}. \tag{22}$$

Finally, from equations 16, 19, 21 and 22 we get

$$\frac{\varepsilon}{v} = t\frac{\partial f}{\partial t} + q\frac{\partial f}{\partial q} - f. \tag{23}$$

Thus far we have used only general thermodynamic principles. Let us now introduce into our reasoning a theorem taken from electromagnetic theory. The theorem that seems best adapted to our purpose is due to Planck and is expressed by the equation

$$g = \frac{q}{c^2}(\varepsilon + pv), \tag{24}$$

where c represents the velocity of light. A simple demonstration of this formula has been given by Hasenöhrl.[1]

From equations 19, 22, 23 and 24 we obtain

$$\frac{\partial f}{\partial q} = \frac{q}{c^2}\left(t\frac{\partial f}{\partial t} + q\frac{\partial f}{\partial q}\right), \tag{25}$$

or

$$\frac{1 - \frac{q^2}{c^2}}{\frac{q}{c^2}}\frac{\partial f}{\partial q} = t\frac{\partial f}{\partial t}. \tag{26}$$

Let us now introduce a new variable s defined by the equation

$$s = \left(1 - \frac{q^2}{c^2}\right)^{\frac{1}{4}}. \tag{27}$$

Then

$$\frac{\partial f}{\partial q} = \frac{\partial f}{\partial s}\frac{ds}{dq} = -\frac{\partial f}{\partial s}\frac{\frac{q}{c^2}}{\left(1 - \frac{q^2}{c^2}\right)^{\frac{1}{4}}}, \tag{28}$$

and equation 26 becomes

$$s\frac{\partial f}{\partial s} + t\frac{\partial f}{\partial t} = 0. \tag{29}$$

[1] F. Hasenöhrl, Zur Thermodynamik bewegter Systeme, Wiener Berichte, vol. 116, 2a, p. 1400, 1907. Cf. M. Abraham, Elektromagnetische Theorie der Strahlung, 2d edition, p. 349, 1908.

From this equation it follows that f must be a homogeneous function of degree zero in t and s; in other words, f is a function of the ratio t/s. Accordingly, equation 19 becomes

$$p = f\left(\frac{t}{\sqrt{1-\frac{q^2}{c^2}}}\right). \tag{30}$$

If we observe that for $q = 0$ this equation must reduce to equation 12, it follows that

$$p = \frac{a}{3}\frac{t^4}{\left(1-\frac{q^2}{c^2}\right)^2}, \tag{31}$$

and equations 21, 22 and 23 enable us to write at once

$$\eta = \frac{4a}{3}\frac{t^3 v}{\left(1-\frac{q^2}{c^2}\right)^2}, \tag{32}$$

$$g = \frac{4a}{3c^2}t^4 v\frac{q}{\left(1-\frac{q^2}{c^2}\right)^3}, \tag{33}$$

$$\varepsilon = \frac{a}{3}t^4 v\frac{3+\frac{q^2}{c^2}}{\left(1-\frac{q^2}{c^2}\right)^3}. \tag{34}$$

Equations 31, 32, 33 and 34 are Planck's equations.

Finally, we observe that since equation 15 can be written in the form

$$d(t\eta + qg - \varepsilon) = \eta dt + pdv + gdq, \tag{35}$$

it follows that if we can express the function $t\eta + qg - \varepsilon$ in terms of t, v, q, its partial derivatives will give us at once η, p, g. This function $t\eta + qg - \varepsilon$ is called by Planck the kinetic potential of the system. If we denote the kinetic potential by h and if we make

use of equations 16 and 31 we get at once

$$h = t\eta + qg - \varepsilon = pv \tag{36}$$

or

$$h = \frac{a}{3}\frac{t^4 v}{\left(1 - \frac{q^2}{c^2}\right)^2}. \tag{37}$$

This equation 37 is also due to Planck. It is easy to verify that

$$\frac{\partial h}{\partial t} = \eta, \quad \frac{\partial h}{\partial v} = p, \quad \frac{\partial h}{\partial q} = g. \tag{38}$$

NEW YORK,
November 20, 1909.

ON WIEN'S DISPLACEMENT LAW.

BY PAUL SAUREL.

IN a previous note we have shown how readily the general principles of thermodynamics lend themselves to the treatment of the problem of a moving hollow space which is the seat of black radiation. In the present note we shall show that the same method can be used to establish Wien's displacement law.

If we consider a hollow space which is the seat of black radiation and if we denote by $\varepsilon, \eta, v, t, p$ the energy, entropy, volume, temperature and pressure of the system, we know that we may write the fundamental thermodynamic equation

$$d\varepsilon = td\eta - pdv.$$

If, however, we suppose that the radiation within the hollow space instead of containing waves of all possible frequencies, contains only waves whose frequencies lie between zero and a certain upper limit ν, then the above equation no longer holds; we must complete it by adding a term which shall correspond to the change in the energy of the system due to a change in the upper limit of frequencies. We are thus led to assume the equation

$$d\varepsilon = td\eta - pdv + \nu dr, \tag{1}$$

where νdr represents the change in the energy of the system when, at constant entropy and constant volume, the upper limit of frequencies is varied. The new variable r which we have thus introduced may be called the radiation of the system.

If now we assume that the energy of the system is a homogeneous function of the first degree of the entropy η, the volume v and the radiation r, we may write

$$\varepsilon = \eta \frac{\partial \varepsilon}{\partial \eta} + v \frac{\partial \varepsilon}{\partial v} + r \frac{\partial \varepsilon}{\partial r}. \tag{2}$$

From equation 1, however, it follows that the partial derivatives in

equation 2 are respectively equal to t, $-p$ and ν. Accordingly, equation 2 becomes

$$\varepsilon = t\eta - pv + \nu r. \tag{3}$$

If we differentiate equation 3 and make use of equation 1 we obtain at once the equation

$$0 = \eta dt - v dp + r d\nu. \tag{4}$$

From this equation it is easy to show that p must be a function of t and ν. Accordingly, we may write

$$p = f(t, \nu). \tag{5}$$

Moreover, since equation 4 can be written in the form

$$dp = \frac{\eta}{v} dt + \frac{r}{v} d\nu, \tag{6}$$

it follows that

$$\frac{\eta}{v} = \frac{\partial f}{\partial t}, \tag{7}$$

$$\frac{r}{v} = \frac{\partial f}{\partial \nu}. \tag{8}$$

Finally, from equations 3, 5, 7 and 8 we get

$$\frac{\varepsilon}{v} = t\frac{\partial f}{\partial t} + \nu\frac{\partial f}{\partial \nu} - f. \tag{9}$$

Let us now introduce the fact that the radiation pressure is equal to one third of the specific energy. Then from the equation

$$p = \frac{1}{3}\frac{\varepsilon}{v} \tag{10}$$

and the equations 5 and 9 we get at once the equation

$$t\frac{\partial f}{\partial t} + \nu\frac{\partial f}{\partial \nu} = 4f. \tag{11}$$

Thus f must be a homogeneous function of the fourth degree in t

and ν. Accordingly, we may change our notation and replace $f(\nu, t)$ by the expression $\nu^4 f(\nu/t)$. Equations 5, 7, 8 and 10 then become

$$p = \nu^4 f\left(\frac{\nu}{t}\right), \tag{12}$$

$$\frac{\eta}{\nu} = \frac{\partial}{\partial t}\left[\nu^4 f\left(\frac{\nu}{t}\right)\right], \tag{13}$$

$$\frac{r}{v} = \frac{\partial}{\partial \nu}\left[\nu^4 f\left(\frac{\nu}{t}\right)\right], \tag{14}$$

$$\frac{\varepsilon}{v} = 3\nu^4 f\left(\frac{\nu}{t}\right). \tag{15}$$

Wien's displacement law now follows at once. From equation 15 we get

$$\frac{\partial}{\partial \nu}\left(\frac{\varepsilon}{v}\right) = \frac{\partial}{\partial \nu}\left[3\nu^4 f\left(\frac{\nu}{t}\right)\right], \tag{16}$$

and if we carry out the indicated differentiation we shall find without difficulty that the right-hand side of the equation is equal to the product of ν^3 by a function of ν/t. Thus we may write

$$\frac{\partial}{\partial \nu}\left(\frac{\varepsilon}{v}\right) = \nu^3 F\left(\frac{\nu}{t}\right). \tag{17}$$

This equation is one of the forms of Wien's law.

NEW YORK,
December 13, 1909.

THE ABSOLUTE VALUES OF THE MOMENTS OF THE ELEMENTARY MAGNETS OF IRON, NICKEL AND MAGNETITE.

By Jakob Kunz.

THE electron theory of magnetism in its present shape based upon the views of Ampere is due to Larmor, M. P. Langevin and P. Weiss. The molecules of a paramagnetic gas under the action of a magnetic field tend to arrange themselves in the direction of the magnetic force, while they are continually deflected by their mutual collisions. If there were no thermal agitation, the maximum intensity of magnetization would be equal to $I_m = N_1 m$, where N_1 represents the number of molecules per unit volume and m the resulting magnetic moment of each molecule. The intensity of magnetization I at a temperature T and under the influence of a magnetic field H is given by the formula

$$\frac{I}{I_m} = \frac{\cosh a}{\sinh a} - \frac{1}{a}, \tag{1}$$

$$a = \frac{mH}{rT}.$$

T is the absolute temperature and $rTN = p$. N is the number of molecules of a gas in unit volume under the pressure p and at the temperature T. Professor P. Weiss expanded the expression (1) by assuming that every molecule of a ferromagnetic substance is acted upon by the surrounding molecules which produce a uniform field $H_m = Ny$, proportional to the intensity of magnetization at the point considered and coinciding in direction with the direction of the magnetization. This internal or intrinsic field has been termed molecular field. It must account for the strong intensity of magnetization in ferromagnetic bodies by means of the laws of paramagnetic bodies in the same way as the internal pressure added to the external pressure accounts for the high density of liquids. An

important analogy has indeed been drawn by P. Curie between, on the one side, the simple law of expansion of a gaseous substance at high temperature and the sudden change which it undergoes on lowering the temperature beyond a critical point so that the mutual attractions of the molecules come into play and produce the liquid state; and on the other side the simple law of magnetization of a substance like iron or nickel at high temperatures and the sudden change which it undergoes when the temperature is lowered beyond the point at which the material passes into its strongly magnetic or ferromagnetic condition. P. Weiss[1] assumes that besides the actions governed by the molecular field the rotations of the molecules in ferromagnetic bodies are as free as the molecules of a gas. Let us suppose that the internal field $H_m = NI$ acts alone without the aid of an external field. The parameter a assumes then the value

$$a = \frac{mNI}{rT}$$

or

$$I = \frac{arT}{mN}. \tag{2}$$

The equation (1) is represented by the curve OA of Fig. 1; the relation (2) is represented by the straight line OA. The intensity of magnetization must conform to the two curves, *i. e.*, for a given temperature T the point of intersection A must have an ordinate equal to the ratio I/I_m. Of course the origin of the coördinates O also satisfies the same condition, but it can be easily shown that the point A corresponds to the stable equilibrium of magnetization. As the paramagnetic susceptibility is very small, enormous magnetic fields would be required to increase this spontaneous magnetization, which is due to the internal field. Reassuming the mechanical analogy the increase of density of a liquid requires external pressures that are incomparably greater than those by means of which the density of a gas is changed. We arrive then at the conclusion that for the absolute temperature T the ordinate AA' represents the saturation value of the intensity of magnetization; or a ferro-

[1] P. Weiss, L'hypothèse du champ moléculaire et la propriété ferromagnétique, Journal de physique, tome VI., 1907, p. 661.

magnetic substance is saturated without the least external field. Though this inference drawn from the theory seems in contradiction with all experimental facts observed, yet it agrees perfectly with the phenomena of magnetization observed in crystals and especially in those of the normal pyrrhotite. This crystal has indeed the very valuable property of a magnetic plane, in which all the elementary magnets are situated. And in this magnet plane appears to be a direction in which saturation takes place almost by itself, at least under very small fields, while a field of about 7,300 units is required to bring about saturation in a perpendicular direction. The supposition of a molecular field accounts indeed, very satisfactorily for the laws that govern the magnetization of the normal pyrrhotite as a function of the external field. The intensity of magnetization as a function of the temperature is a very complicated phenomenon, varying from one substance to the other, and varying also with the magnetic field for the same substance and it appears doubtful whether the most simple hypothesis of the uniform molecular magnetic field is able to account for all the phenomena observed. In the case of magnetite, however, P. Weiss has shown that the theoretical curve coincides exactly with the experimental curve between the temperatures: -79 and $+587°$. On the assumption that a piece of ordinary iron is composed of small crystals having the property of a magnetic plane P. Weiss has shown in addition that the loops of hysteresis of annealed iron can be given a theoretical interpretation.

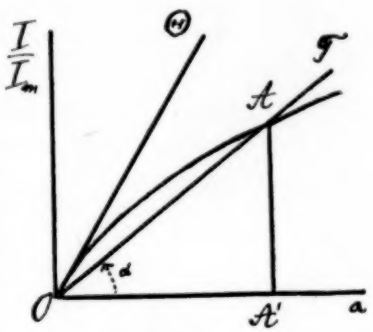

Fig. 1.

In order to determine the absolute values of the internal magnetic field, we have to examine the magnetic properties of the ferromagnetic substances in the neighborhood of the point where the spontaneous magnetization disappears. Thus iron loses the spontaneous magnetization at a temperature of 756° C. Between this point and 920°, the iron has still a considerable susceptibility, the mag-

netism appearing however only under the combined action of the external and internal field. In this region we have

$$a = \frac{m(H_e + NI)}{rT},$$

$$T = \frac{m(H_e + NI)}{ar}, \tag{4}$$

$$\frac{I}{I_m} = \operatorname{cotgh} a - \frac{1}{a} = \sum (-1)^{n-1} \cdot 2^{2n} \cdot B_{2n-1} a^{2n-1}/(2n)!$$

$$= \frac{1}{3} a - \frac{2}{90} a^3 + \frac{4}{45 \cdot 42} a^5 - \cdots.$$

$B_1, B_2, B_3 \cdots$ are the numbers of Euler and Bernoulli.

As long as we consider only the beginning of the curve OB of Fig. 1, whose tangent through the origin corresponds to the temperature $\theta = 756 + 273 = 1029$, we may consider only the first term on the right-hand side of the last equation.

$$\frac{I}{I_m} = \frac{a}{3}.$$

Up to the temperature θ we have

$$a = \frac{mNI}{rT}.$$

Replacing in this expression I by $I_m \cdot a/3$ and T by θ we get

$$a = \frac{mNI_m a}{3r\theta},$$

hence

$$\theta = \frac{mNI_m}{3r}. \tag{3}$$

Dividing (4) by (3) we find

$$\frac{T}{\theta} = \frac{3H_e}{aNI_m} + \frac{3}{a}\frac{I}{I_m}$$

or

$$\frac{T}{\theta} = \frac{3}{a}\frac{H_e}{NI_m} + 1,$$

$$\frac{T-\theta}{\theta}=\frac{H_e}{NI},$$

$$(T-\theta)I=\frac{\theta H_e}{N}.$$

This equation represents an equilateral hyperbola and allows us to determine the coefficient N. It is however more convenient to proceed in the following way: The coefficient of specific magnetization χ for paramagnetic bodies is inversely proportional to the absolute temperature, according to Curie's law.

$$C=\chi T=T\frac{k}{d}.$$

k is the paramagnetic susceptibility and d the density of the substance.

At a temperature a little above θ the ferromagnetic properties appear only if an external field H_e coöperates with the molecular field. The apparent susceptibility given by the experiment is equal to

$$k'=\frac{I}{H_e}.$$

The real susceptibility however is equal to

$$k=\frac{I}{H_e+NI}, \quad k'>k,$$

$$\frac{1}{k'}=\frac{H_e}{I}; \quad \frac{1}{k}=\frac{H_e+NI}{I},$$

$$\frac{1}{k}=\frac{1}{k'}+N.$$

If we approach θ from lower temperatures H_e is insignificant in comparison with NI, therefore we have for $T=\theta$

$$k=\frac{I}{NI}=\frac{1}{N}.$$

Curie's law applied for the temperature θ gives the expression

$$\frac{k}{d}\theta=C,$$

$$\theta=\frac{d\cdot C}{k}=d\cdot C\cdot N.$$

At a temperature T above θ, where the iron appears to be paramagnetic, we have

$$C = \frac{T \cdot k}{d},$$

$$\frac{1}{k} = \frac{T}{C \cdot d}.$$

Now we find

$$\frac{1}{k} = \frac{1}{k'} + \frac{\theta}{Cd} = \frac{T}{Cd},$$

$$C = \frac{k'(T - \theta)}{d}.$$

Observing corresponding values of k' and T we find C and from $\theta = d \cdot C \cdot N$ we find N. In this way P. Weiss [1] found for

iron :	$N = 3{,}850,$	$H_m = NI = 6{,}560{,}000,$
nickel :	$N = 12{,}700,$	$H_m = NI = 6{,}350{,}000,$
magnetite :	$N = 33{,}200,$	$H_m = NI = 14{,}300{,}000.$

If the molecular magnets act upon one another with magnetic forces of this enormous amount, then the potential energy due to the molecular magnetic field must have considerable values.

$$E = -\tfrac{1}{2}IH, \quad H = NI,$$

$$E = -\tfrac{1}{2}NI^2.$$

In the state of stable equilibrium this energy must be a minimum, or negative. If the temperature of a ferromagnetic body is raised from a lower value to a point θ where the spontaneous ferromagnetism disappears, an amount of energy equal to $\frac{1}{2}NI^2$ will gradually be absorbed, therefore the specific heat appears to be greater than it would be without the increase of the ferromagnetic energy. In the case of iron we have $\frac{1}{2}NI^2 = 5.58 \cdot 10^9$ ergs per cm.^{3} $= 7.08 \cdot 10^8$ ergs per gram.

The amount of heat absorbed is equal to

$$q_m = \frac{7.08 \cdot 10^8}{4.19 \cdot 10^7} = 16.8 \text{ calories.}$$

[1] P. Weiss et P. Beck, Chaleur spécific et champ moléculaire des substances ferromagnétiques, Journal de physique, tome 7, p. 249, 1908.

Now we have

$$\int_{\tau}^{\theta} c_m dt = q_m,$$

$$c_m = \frac{dq_m}{dt} = \frac{1}{2}\frac{NdI^2}{yd},$$

$$y = 4.19 \cdot 10^7, \quad d = \text{density}.$$

As the intensity of magnetization is known as a function of the temperature, we can determine dI^2/dt and calculate cm. for each temperature. This has been done by P. Weiss and Beck and they found a very satisfactory agreement between the calculated apparent specific heat and the changes that occur in the specific heat with increasing temperature, up to θ. The apparent specific heat c_m due to the disappearing molecular magnetic field in the neighborhood of $\theta = 756$ for iron is equal to 0.136 and the abrupt change of specific heat at the same point is equal to 0.112. Thus the theory of the intrinsic magnetic field agrees at least in four different directions very well with the phenomena observed.

I am going to draw from the above theory a further conclusion, which will prove to be in perfect agreement with the fundamental quantities of nature.

The electron theory of ferromagnetism gives us a means of determining the moment m of the molecular magnets of those substances whose internal magnetic field has been determined. We can apply several equations, but there is one expression which gives a very simple way to determine m. Let us apply the equation

$$a = \frac{mNI}{rT},$$

for the absolute temperature θ where the relation holds

$$\frac{I}{I_m} = \frac{a}{3}.$$

We find

$$a = \frac{mNI_m a}{3rT},$$

$$m = \frac{3r\theta}{NI_m}$$

θ is the temperature where the ferromagnetism disappears, r is given by the equation of gases

$$rN_1T = p,$$
$$p = 1.01 \cdot 10^6, \quad T = 273, \quad N_1 = 2.7 \cdot 10^{19},$$
$$r = 1.36 \cdot 10^{-16}.$$

I_m is the saturation value of the intensity of magnetization at the absolute zero of temperature. I_m has to be determined from the above theory by means of the value I, intensity of magnetization for the case of saturation at the temperature $t°$.

In the case of iron we have

$$I = 1{,}850, \quad I_m = 2{,}120, \quad N = 3{,}850, \quad \theta = 756 + 273 = 1{,}029,$$
$$m = 5.15 \cdot 10^{-20} \text{ absolute electromagnetic units.}$$

Let N_1 be the number of molecular magnets in unit volume at the absolute zero, then we have:

$$N_1 m = I_m = 2{,}120,$$
$$N_1 = 4.12 \cdot 10^{22}.$$

If this number N_1 of the elementary magnets is at the same time the number of molecules of iron, and if the mass of 1 molecule of iron is equal to μ we have:

$$N_1 \mu = \delta = 7.86,$$

where δ is the density of iron at the absolute zero.

$$\mu = \frac{\delta}{N_1} = 1.91 \cdot 10^{-22} \text{ gr.}$$

If the molecule of iron consists of two atoms, it will be 111.8 times heavier than the atom of hydrogen, and the mass of the atom of hydrogen μ_H will be equal to

$$\mu_H = \frac{1.91 \cdot 10^{-22}}{111.8} = 1.66 \cdot 10^{-24} \text{ gr.}$$

A recent value of this quantity has been determined by Rutherford who found

$$\mu_H = 1.61 \cdot 10^{-24} \text{ gr.}$$

from radioactive phenomena. The coincidence of the values of 1 atom of hydrogen deduced from so very different phenomena as those of radioactivity and ferromagnetism by very different considerations, is a strong evidence in favor of the theories involved. It follows immediately that the molecular magnet of iron contains two atoms. In the case of magnetite we find the following numbers:

$$N = 33{,}200,$$
$$\delta = 5.2,$$
$$I = 430, \quad I_m = 490.$$

According to Curie $\theta = 536 + 273 = 809$.
According to Weiss $\theta = 589 + 273 = 862$.

$$m = 2.02 \cdot 10^{-20},$$
$$N_1 m = I_m = 490,$$
$$N_1 = 2.42 \cdot 10^{22}.$$

If the mass of each molecule is equal to μ we have

$$N_1 \mu = 5.2,$$
$$\mu = 2.15 \cdot 10^{-22},$$
$$Fe_3O_4 = 231.7,$$

accordingly

$$\mu_H = \frac{2.15 \cdot 10^{-22}}{231.7} = 0.93 \cdot 10^{-24} \text{ gr.};$$

a value that agrees pretty well with that derived from the kinetic theory of gases.

Taking for θ Weiss' value I find for μ_H

$$\mu_H = 0.99 \cdot 10^{-24}.$$

In the case of nickel I find the following numbers:

$$N = 12{,}700, \quad I = 500, \quad I_m = 570, \quad \theta = 376 + 273 = 649,$$
$$m = 3.65 \cdot 10^{-20},$$
$$N_1 m = I_m,$$
$$N_1 = 1.56 \cdot 10^{22},$$
$$N_1 \mu = \delta = 8.8 \quad \mu = 5.63 \cdot 10^{-22}.$$

The atomic weight of nickel is equal to 58.7, hence, assuming that each molecular magnet contains two atoms, we find

$$\mu_H = \frac{\mu}{117.4} = 4.8 \cdot 10^{-24},$$

a value that is exactly three times bigger than that given by Rutherford. As the degree of accuracy is the same in the case of iron, nickel and magnetite we have to admit that the molecular magnet of nickel is made up of 6 atoms.

The quantities considered are given in the following table:

Substance.	$I_{t=20^0}$	I_m	Θ	N	$NI=H_m$	$m10^{20}$	$\mu_H \cdot 10^{24}$
Fe	1,860	2,120	756	3,850	6,560,000	5.15	1.66
Fe_3O_4	430	490	536?	33,200	14,300,000	2.02	0.93
Ni	500	570	376	12,700	6,350,000	3.65	4.8

As the ratio of the density of nickel and iron 1.12 is nearly equal to the ratio of the atomic weights 1.05 of the two meatls, the number of molecules per unit volume must be the same for both metals, assuming that each molecule contains two atoms. And as the moment of the molecular magnets of nickel is only 29 per cent. smaller than that of iron we should expect that the intensity of magnetization of nickel varies only about 30 per cent. from that of iron, while in fact the magnetization of iron is 3.7 times superior to that of nickel; this consideration indicates again, that either the molecular magnet of nickel contains 6 atoms or only every third molecule is an elementary magnet. This fundamental difference in the molecular magnets of iron and nickel must be taken into account, when some very interesting differences in the magnetic behavior of the two metals have to be explained. Thus the first layer of electrolytically deposited nickel is stronger magnetically than the subsequent layers, while for iron the opposite statement is true. In addition a longitudinal compression decreases the magnetization of iron and increases that of nickel, while a longitudinal pull increases the magnetization of iron and decreases that of nickel.

The discussion of the molecular magnetic field in terms of the electron theory offers some difficulties, which, however, are not of

such a nature as to involve contradictions to other theories. If $4.12 \cdot 10^{22}$ molecules of iron are contained in unit volume, the radius of one molecule cannot be much bigger than $1.5 \cdot 10^{-8}$ cm. $= r$.

We may try to determine the velocity v of an electron in its orbit by means of the equation

$$\frac{mv^2}{r} = \frac{e^2}{r^2},$$

m being the mass and e the charge of an electron.

$$m = 8.77 \cdot 10^{-28}, \quad e = 4.65 \cdot 10^{-10},$$

$$v = 1.3 \cdot 10^8 = \frac{2\pi r}{T} = 2\pi r n_1.$$

n_1 is the frequency of the electron.

$$n_1 = 1.4 \cdot 10^{15},$$

a frequency bigger than that of sodium light $5.1 \cdot 10^{14}$.

The magnetic moment m_1 due to the revolution of

$$1 \text{ electron} = \Phi i = \pi r^2 \frac{e}{T} = \pi r^2 e n_1 = 1.54 \cdot 10^{-20}.$$

Thus one electron alone, revolving with high frequency, is able to produce a magnetic moment of the right order of magnitude. The magnetic force however under the given circumstances in the center of the electronic orbit is equal to

$$h_1 = \frac{2\pi i}{r} = \frac{2\pi e n_1}{r} = 8{,}800,$$

a value about 1,000 times smaller than the molecular magnetic field. If each electron would produce a field of this magnitude, we can see that even in this case of a rather weak elementary field a large number of surrounding molecules would contribute to the molecular field of the central molecule. Let a be the distance of a point on the axis of the orbit of the electron from the center of the orbit, then the magnetic force in that point a will be equal to

$$h_a = \frac{2\pi i r^2}{\sqrt{a^2 + r^2}^3} = \frac{hr^3}{\sqrt{a^2 + r^2}^3} = h\left(\frac{r}{a}\right)^3,$$

if we put approximately $a = 10r$,

$$h_a = 8.8.$$

Thus even in a distance $a = 20r$ the magnetic field will still be appreciable, and the sphere of activity will still be larger if the magnetic field, due to one molecule, is superior to that of 8,800 units. If the frequency $n_1 = 1.4 \cdot 10^{15}$ would be the real one, the iron should emit even at the absolute zero of temperature a radiation of a frequency higher than that of sodium light. We have therefore to admit that the frequency of the electrons producing the magnetic properties is much smaller. If we assume $n_2 = 0.5 \cdot 10^{13}$ corresponding to a wave-length of ultra-red light $\lambda = 6 \cdot 10^{-3}$ cm., we find

$$h = 31\,; \quad m = 5.5 \cdot 10^{-23},$$

values that are too small.

If there were N revolving electrons in a molecule contributing to the magnetic moment m would be equal to

$$m = r^2 \pi e n N,$$

$$h = \frac{2\pi}{r} e n N.$$

URBANA, ILLINOIS,
October 7, 1909.

ON CONTACT DIFFERENCE OF POTENTIAL IN A MAGNETIC FIELD.

By E. P. Adams.

ABOUT two years ago the writer made some experiments to determine whether the contact difference of potential between pairs of metals is changed in the presence of a magnetic field. The line of reasoning which led to the thought that such an effect might exist will first be given.

It seems well established that the contact difference of potential between metals in air is a chemical effect, the result of differential chemical action between the metals and condensed air films on their surfaces. At any rate it seems certain that these air films are essential in order that the contact difference of potential may be developed. There is another way of looking at the subject which may be worth some attention. The fundamental thing to be explained is that the potential of an insulated metal differs from that of the surrounding air; and that this difference of potential varies from metal to metal. Let us assume that each unit area of the surface of the metals emits in unit time N electrically charged particles, each of mass m and charge e. The metal is further supposed to be coated with a thin film of condensed air, or other substance, with the very high transverse electric resistance R per unit surface. The charged particles must be supposed to be emitted from the metal with an initial velocity sufficient to carry them through the film. A difference of potential V is thus set up between the two sides of the film. In the steady state the electric current due to the flow of charged particles from the metal through the film is balanced by the conduction current, the result of the difference of potential V and the conductivity $1/R$ of the film. Therefore,

$$Ne = V/R$$

or

$$V = NeR.$$

Both N and R may be supposed to vary with the metal. Thus each insulated metal will be at a definite potential above or below that of the surrounding air, and this is required according to our present views concerning the contact difference of potential between metals.

Suppose next that the metal in the form of a disc is placed in a magnetic field parallel to its plane. The charged particles will tend to describe circular paths whose radius of curvature is given by

$$\frac{mv^2}{\rho} = Hev$$

or

$$\rho = \frac{mv}{He},$$

v being the velocity of the particle and H the magnetic force. If this radius of curvature is small enough some of the particles will be prevented from getting through the film; the difference of potential between the two sides of the film will be diminished, and thus the contact difference of potential between a pair of metals, which is all that can be measured, will be changed.

The results of the experiments, which will be described, were decisively negative. The sensitiveness of the method employed was such that a change of 0.001 volt in the contact difference of potential could have been observed. The matter was therefore dropped as it was thought that negative results of an experiment of this kind were not of sufficient value to justify their publication.

Very recently, however, M. V. Posejpal [1] has published the results of some experiments, a part of which bear upon this same problem. Contrary to the results of the writer, M. Posejpal finds that the contact difference of potential between iron and zinc is changed in a magnetic field; since the method he employed is quite different from that of the writer it may be worth while now briefly to describe the experiments of the latter in order that a comparison of results may be made.

The compensation method devised by Lord Kelvin was employed. In the accompanying diagram A and B represent the two metallic discs the contact difference of potential between which is

[1] Annales de Chimie et de Physique, August, 1909.

to be measured. These are screwed on to the brass ends of the hard rubber insulators *R*, *R*, which are carried on brass rods, and these in turn freely slide through fixed brass tubes, as shown. The lower rod is fixed in position, its height being adjusted by means of a set screw. The limits of motion of the upper rod are controlled by the adjustable collars *I*, *I*.

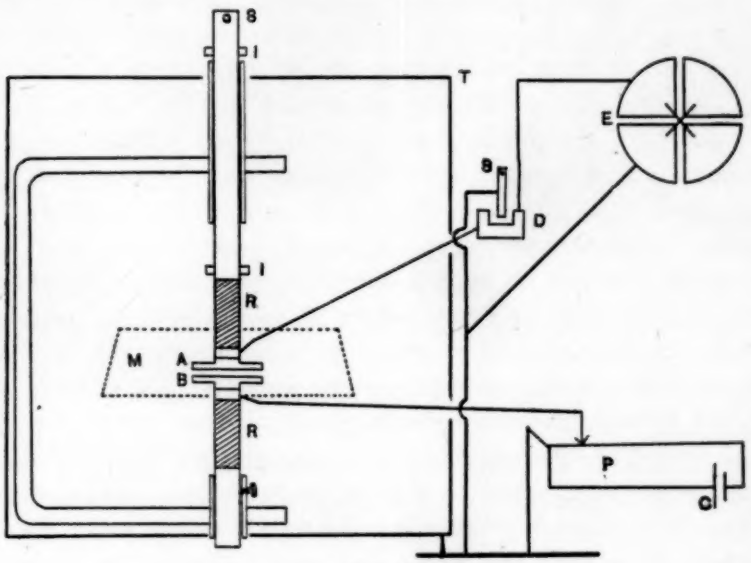

Fig. 1.

The upper disc is permanently connected to one pair of quadrants of the electrometer, *E*. By means of the mercury key *D*, this pair of quadrants may be connected to earth. When the rod *S* is raised the earth connection is broken. The other pair of quadrants is connected to earth. The lower disc *B* is connected to the slider of the potentiometer *P*, so that it may be kept at any desired potential. Strings are attached to *S*, *S* by means of which the earth connection of the first pair of quadrants may be broken and the upper disc raised at the observing telescope.

The determination of the contact difference of potential is made as follows: the electrometer quadrants being earthed, the two discs are brought close together, but not touching. Electrically they are of course in contact. The earth connection is then broken and

the upper disc raised. A deflection of the electrometer needle, in general, results. The potential of the lower disc is then changed until on repetition of the above process no deflection of the electrometer results. The potential applied to the lower disc is then the contact difference of potential between the two discs.

An estimate can easily be formed of the sensitiveness of this method. Let the capacity of the condenser formed by the two discs when close together be c and when separated, c'. If the lower disc be kept at zero potential by connecting it to earth the quantity of electricity set free on raising the upper disc is $V(c - c')$, V being the contact difference of potential. This quantity divides between the electrometer and disc condenser, so that $V(c - c') = v(C + c')$, where v is the potential to which the insulated quadrants are raised. c' is small compared to C and to c, so that $v = Vc/C$. The discs were 19 millimeters in diameter; their distance when near together was approximately 0.2 mm., and when separated something over 1 cm. The capacity of the electrometer and connections was approximately 90. Hence considering the disc condenser as a simple parallel plate condenser, we find $v = V/8$. The electrometer had a sensitiveness of about 8,000 divisions per volt. Hence a deflection of one scale-division corresponds to a contact difference of potential of 0.001 volt. Direct experiment showed that when the contact difference of potential between the two discs was balanced by the potential applied to the lower a change of 0.001 volt in the latter produced a distinct deflection.

The pole-pieces of the electro-magnet, one of which is shown in section at M, projected through holes cut into opposite sides of a zinc box T, which completely shielded the interior. As a further precaution against outside electrostatic disturbances the pole-pieces themselves were earthed. The electrometer connections were run through earthed brass tubes.

The electrometer used was of the Dolezalek type; the needle suspension was a platinum wire, 0.0004 inch in diameter through which the needle was kept at a potential of about 80 volts by means of a battery of small storage cells. A Wolff potentiometer with five dials and a total resistance of 15,000 ohms was employed. The

current for it was supplied by a cadmium storage cell for which the writer is indebted to Professor Hulett.[1] The electromotive force of this cell was tested from time to time by comparison with a standard cell and proved to be remarkably constant.

The discs used were made of iron, zinc, and gold- and platinum-plated brass. After the discs were cleaned and screwed into position the contact difference between them changed rapidly; but after the course of an hour or so it became so constant that no change could be detected during a period of ten to fifteen minutes. During this stage the contact difference was measured, then the magnetic field was applied and the contact difference again measured, and a final measurement was made after the magnetizing current was broken. Many repetitions of this were made, using the combinations gold-zinc, platinum-zinc, and gold-iron, but in no case was the slightest effect of the magnetic field observed. The magnetic force was measured by a calibrated bismuth spiral and was approximately 4,800 electromagnetic units.

The conclusion thus followed: the effect of a uniform magnetic field of 4,800 units, if any, on the contact difference of potential between pairs of these metals is certainly less than 0.001 volt.

The experiments of M. Posejpal already referred to differ in at least three important respects from those just described. In the first place, he used a direct deflection method, instead of a null method, which necessarily involved greater possibility of error. In the second place the two discs were allowed to come into actual contact with each other before separation. It seems possible that the observed effects resulted from this actual contact. The contact difference of potential between metals is extremely sensitive to changes in their surfaces. If one of the discs is allowed to fall on the other considerable changes in the contact difference are almost certain to result. The writer has observed that if the initial distance between the two discs was made so small that on dropping the upper disc it touched the lower one, due to a lack of rigidity in the support, a distinct change in the contact difference was found on the next measurement. M. Posejpal found that the contact difference was by no means constant and sought to get correct values by tak-

[1] PHYS. REV., 1908, 27, p. 33.

ing the average of many results. Now when a magnetic field is applied this mechanical effect would be altered, particularly in M. Posejpal's experiments since he used only the combination zinc-iron. The iron, unless very firmly held, would be certain to move in the magnetic field, and thus a secondary effect of the magnetic field on the contact difference of potential might be expected to result. Furthermore, when two unlike metals are separated from contact one would expect a production of frictional electricity, which of course would be added to the electricity set free by the true contact difference of potential. In the magnetic field, due to mechanical action on the iron, the amount of frictional electricity would be altered, and thus a change in the apparent contact difference of potential would result.

The third difference between the two methods lies in the position of the two discs with respect to the magnetic field. In M. Posejpal's experiment the lower disc remained in the region of strong magnetic force, while the upper disc was pulled into a region of comparatively weak magnetic force. In the writer's experiment, the pole faces of the magnet were of such a size that both discs remained in a fairly uniform field even after the upper disc was raised. Whether an explanation of the results obtained lies in this fact or not can be tested only by experiment.

Unfortunately, M. Posejpal does not state the strength of the magnetic field he employed, nor the diameter of the discs. But the large effects he obtained, combined with the comparative insensitiveness of his method (his electrometer gave only 60 divisions for a volt), make it improbable that his positive results were due to using a magnetic field of much greater strength than that used by the writer.

PRINCETON, N. J.

THE EFFECT OF TEMPERATURE ON FLUORESCENCE AND ABSORPTION.

By R. C. Gibbs.

II. Fluorescence and Absorption of Canary Glass at Low Temperatures.[1]

THE study of the fluorescence and absorption of canary glass at low temperatures is a continuation of a similar investigation made with the same specimen at high temperatures.[2]

The substances used in making the glass are: SiO_2 70 per cent., K_2O 24 per cent., CaO 6 per cent. to which 2.5 to 3.0 per cent. sodium uranate is added.

The specimen, ground to the shape of a rectangular plinth 3.37 cm. by 2.88 cm. by .74 cm., was mounted in the same iron case as was used for the high temperatures, the plan, front elevation and end elevation of which are shown in Fig. 9. The heavy broken

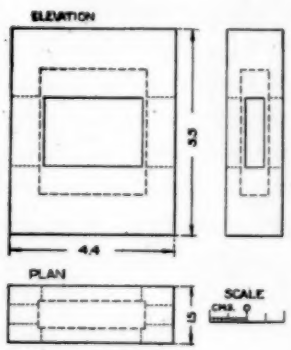

Fig. 9.

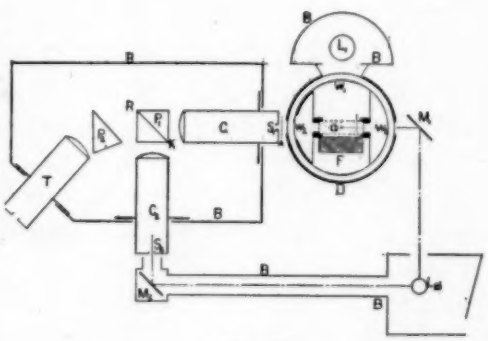

Fig. 10.

lines indicate the position of the glass. The measurements were made with a Lummer and Brodhun spectrophotometer which together with the remaining apparatus is shown in Fig. 10.

[1] A summary of the work described in this paper was presented to the British Association for the Advancement of Science at its Winnipeg meeting August, 1909.

[2] Gibbs, R. C., Phys. Rev., Vol. XXVIII., No. 5, p. 361.

The iron case the corners of which are indicated by the heavy marks and which contained the specimen of glass G was securely fastened to a fiber rod F and the whole rigidly supported inside of an upright unsilvered cylindrical Dewar bulb D. Cardboard covered with black paper and fastened to the iron case extended to the walls of the Dewar as shown by four light lines. The heavy lines inside and outside the bulb represent black paper so arranged as to leave three windows W_1, W_2 and W_3 through which light may pass in or out of the bulb.

To excite fluorescence a Cooper-Hewitt mercury lamp L_1 was used, the light from which passed through window W_1. The fluorescent light passing through window W_2 fell upon slit S_1 of collimator C_1. For a standard of comparison light from an acetylene flame L_2 was reflected by a block of magnesium carbonate M_2 upon slit S_2 of collimator C_2. The lines marked B represent screens which for the most part were covered with black paper.

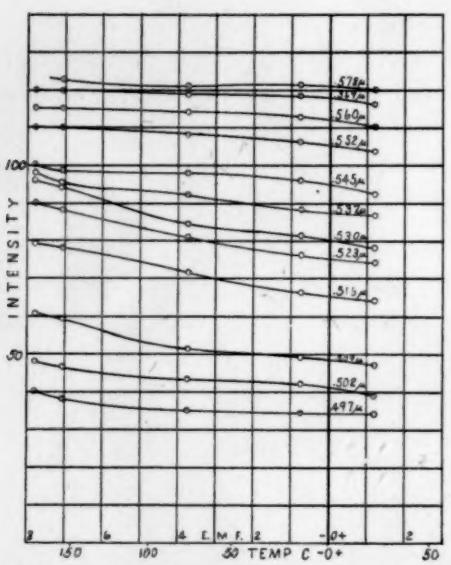

Fig. 11. Showing effect of temperature on transmission intensity for various wave-lengths.

For determining the absorption, light from L_2 was reflected through W_3 by a glass mirror M_1. The transmitted light fell upon slit S_1. For the purpose of securing a uniform field a ground glass A was inserted in front of the slit. For a comparison light the same arrangement as in the case of the fluorescence was used. To obtain the incident light a set of readings was made with the glass G removed.

In all the measurements slit S_1 was kept at a constant width of .5 mm. and readings were taken by varying the slit S_2 until the intensities of light from the two sources were equal.

The upper part of the Dewar bulb was packed with wool and cooling was secured by pumping liquid air into the bottom of the bulb a little at a time. In this way the temperature was kept from varying more than 2° C. during any particular set of observations through the spectrum. A much greater uniformity could be secured by this method if required. The temperature was measured by means of an iron-constantan thermo-junction and a potentiometer.

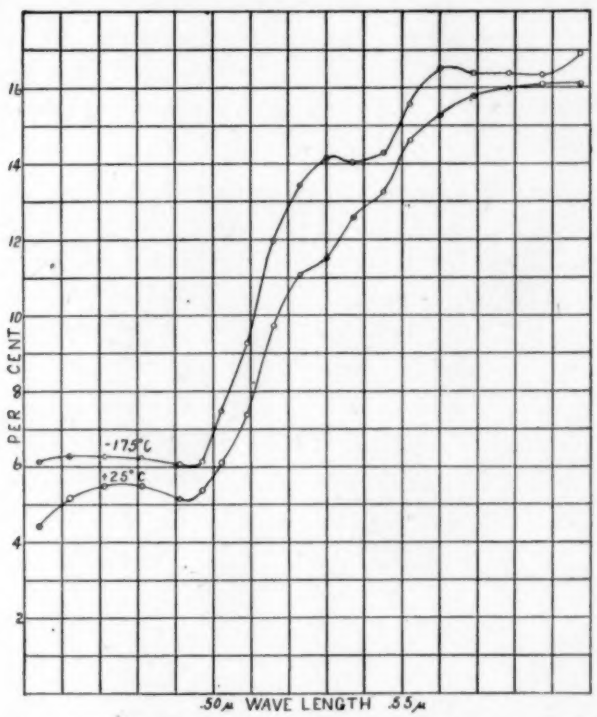

Fig. 12. Showing percentage transmission at + 25° C. and — 175° C.

The equation for the E.M.F. of the junction was determined by reference to three fairly well separated fixed temperatures. The E.M.F. for several other temperatures were determined from this equation and a curve plotted which checked very well with other observed values of E.M.F. and known temperatures.

During all of the observations one face of the glass was visible and it was carefully watched for any sign of moisture or frost on its surface. In order to eliminate the formation of moisture on the

outside walls of the bulb through which light passed, heating coils were placed in contact with the blub below each of the three windows W_1, W_2 and W_3 so that the glass in those regions was kept well above the dew point.

The transmission intensities for the more important wave-lengths are shown in Fig. 11. The increase due to a lowering of temperature is general throughout the spectrum, the rate of increase being largest on the boundary of the absorption band, *i. e.*, from .502 μ to about .537 μ as may be seen by reference to Fig. 12.

From the curves in Fig. 11 and others not there shown, the transmission intensities were read off at temperature intervals of 40 degrees from 25° C. to — 175° C.

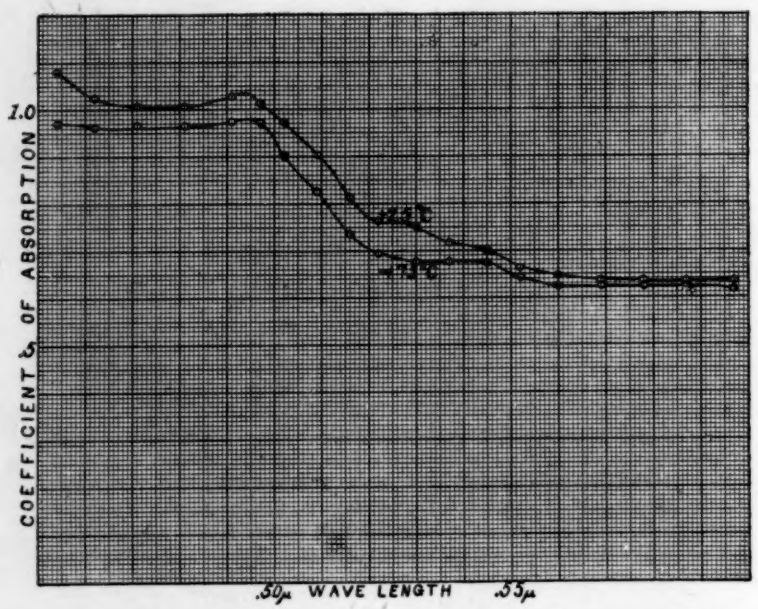

Fig. 13. Showing the coefficient of absorption at + 25° C. and — 175° C.

The percentage transmission, *i. e.*, the ratio of the incident light to the graphically determined transmitted light is shown in Fig. 12 for the highest and lowest temperatures, from which it may be seen that lowering the temperature produces a slight shift of the boundary of the main absorption band toward the shorter wave-lengths. It is to be noticed that the absorption is rather large in all parts of the

spectrum and that the rather large scale to which these curves are plotted somewhat exaggerates their irregularities. This is especially true for the curve at $-175°$ between .53 μ and .55 μ. That the presence of this small absorption band is however not due to error in measurements at this temperature is evidenced by the fact that similar curves for the intermediate temperatures show its gradual development.

In Fig. 13 is shown the effect of a decrease of temperature on the coefficient of absorption (β) as computed from the following formula.

$$\beta = \frac{\log I - \log T}{x}$$

wherein I represents incident light, T transmitted light and x the thickness through which the light passes.

The observed fluorescence intensities for the majority of the wave-lengths measured are shown in Fig. 14. From these curves were read off the intensities for the same temperatures as in the case of transmission. In order to obtain the values for the lowest temperature these curves had to be slightly exterpolated but with the two lowest observed temperatures rather close together such a procedure seemed to be justified. From these values of fluorescence and the coefficients of absorption the fluorescence corrected for absorption was computed according to a formula derived in a previous article to which a reference was made at the

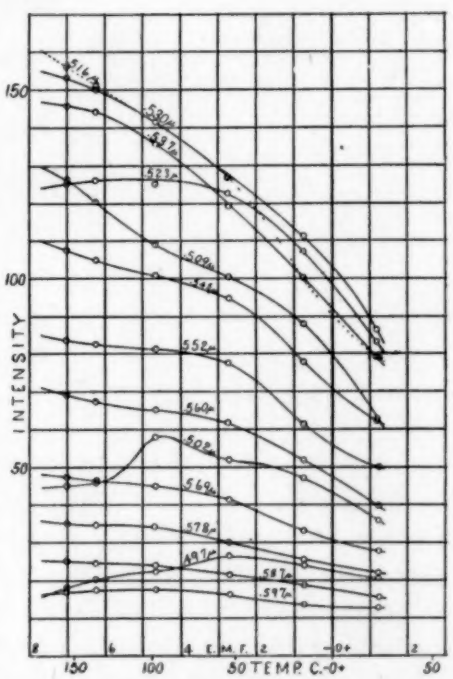

Fig. 14. Showing effect of temperature on fluorescence intensity for various wave-lengths.

beginning of this paper. The results obtained from such computations are seen in the typical fluorescence curves shown in Fig. 15.

The rather broad fluorescence band at room temperature seems to show a slight indication of being made up of two overlapping bands

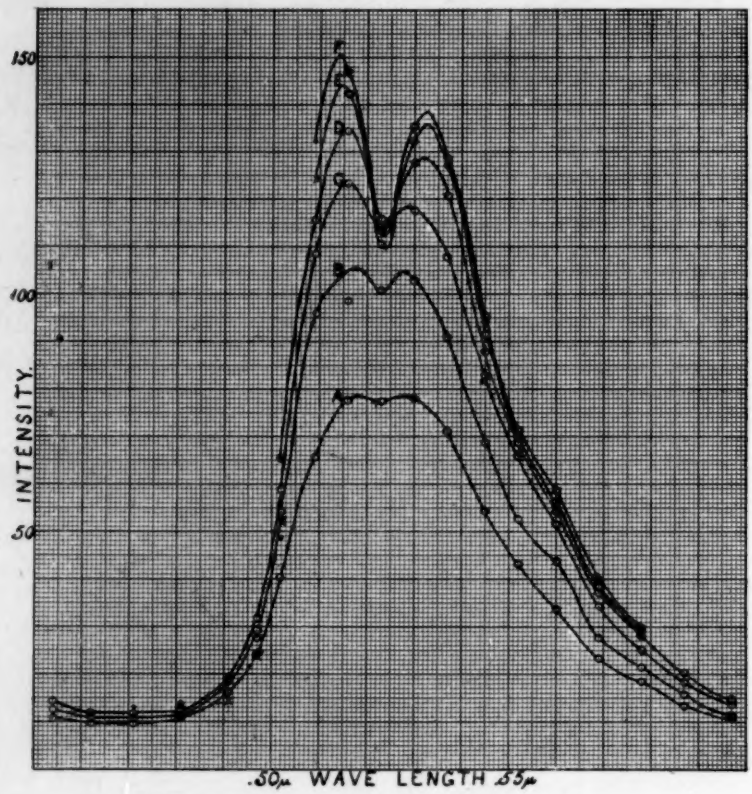

Fig. 15. Fluorescence corrected for absorption.

Curve *A*, +25°; *B*, −15°; *C*, −55°; *D*, −95°; *E*, −135°; *F*, −175° C.

with their maxima very near together. The band shades off a little more gradually on the side of the longer wave-lengths. On cooling the two bands develop very distinctly, the intensity increases, for the most part, throughout the fluorescent region and the curves become very much steeper especially on the side of the shorter wave-lengths. The two maxima gradually separate, one shifting toward the longer wave-lengths and the other in the opposite direction. The minimum which develops between the two bands increases at

first and then gradually decreases. The order of increasing values of the intensity for that region is as follows: Curve *A*, + 25° ; *B*, − 15° ; *F*, − 175° ; *E*, − 135° ; *C*, − 55° ; *D*, − 95° C.

On the side of the shorter wave-lengths the curves (Fig. 15) for the three lowest temperatures are not completed because they would cross the curves already drawn and make it hard to distinguish one from another. Some of the points for these curves are included, and by referring to the various marks used in plotting the last point through which each of these curves is drawn, one may readily see approximately their position.

The general increase in fluorescence intensity with decreasing temperature agrees with the results secured for increasing temperatures above that of the room. The typical fluorescence at room temperature obtained in connection with the higher temperatures, observations for which were made a year before, differs somewhat from that shown here. The curve for the former shows a maximum at .537 μ with a somewhat irregular decrease toward the violet end. There are two possible explanations for this difference. Probably the glass is not strictly homogeneous and in all likelihood the slit of the spectrophotometer was not placed exactly opposite the same part of the glass in the two sets of observations. A much more probable explanation is that the glass has gradually recovered from the effect of heating. It was noted in the previous article on high temperatures that the intensity of fluorescence at room temperature was larger a day or so after heating when under excitation, than before but that a general recovery resulted if allowed to stand. Two or three weeks seemed to be sufficient for the greater part of the spectrum. The shape of the crest of the room temperature curve shown here agrees more closely with that obtained before the glass was heated than with any of the others obtained a relatively short time after heating. It may be well to add here that this specimen did not show phosphorescence.

The bands which develop on cooling with maxima at .514 μ and .533 μ respectively, showing an increase in intensity of about 100 per cent., seem to be the same bands which were practically destroyed by a temperature of 350° C. The fact that there is no evidence at the lower temperatures of a band at about .545 μ which

persisted at the higher temperatures together with the position and development of the two bands at the lower temperatures strengthens the assumption that the band at .454 μ was slightly increased, if not entirely developed, by heating. The latter suggestion is supported by the fact that the fluorescence at room temperature measured shortly after cooling showed very little variation from that measured at the same temperature a few days before cooling.

Summary.

The essential results of the above recorded observations may be stated as follows:

1. Decrease of temperature produces a decrease in the absorption throughout that region of the spectrum measured and a corresponding narrowing of the absorption band, a result consistent with the effect of increasing temperatures.

2. The main portion of the rather broad fluorescence band in the yellow-green portion of the spectrum increases very decidedly on cooling and breaks up into two narrow overlapping bands very close together.

3. On the side of the shorter wave-lengths the fluorescence intensity decreases at the extreme low temperatures thus narrowing the band on that side.

4. The fluorescence bands which develop on cooling appear to be the same ones which were practically destroyed at the higher temperatures and the band which persisted at the higher temperatures has been destroyed by cooling or else did not exist at room temperature.

5. The fluorescence of this specimen evidently depends, to a more or less small extent, upon the previous heat treatment and the period of recovery to normal fluorescence may extend over a considerable time.

Physical Laboratory,
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SOME PHOTO-ELECTRIC PROPERTIES OF THE ALKALI METALS.

III. The Dependence of Photo-Electric Current on the Wave-Length of the Incident Light.[1]

By F. K. Richtmyer.

SOON after the discovery that the alkali metals were photo-active in the visible spectrum Elster and Geitel[2] published some brief observations showing the sensibility of these metals for different colors. These data however were qualitative rather than quantitative, and as the exact nature of the relation between wave-length and photo-electric current would not only be of value in the theory of

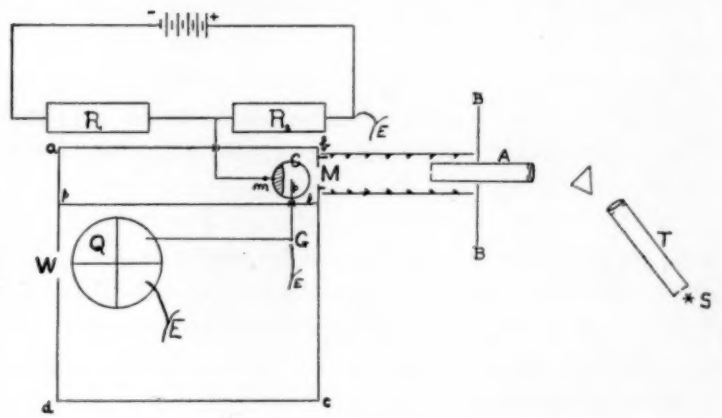

Fig. 1.

photo-electric phenomena, but would also help in correlating it with other phenomena, the writer has attempted the determination of this relation for sodium — which has a maximum of sensibility in the visible spectrum.

The apparatus used has already been described in the first article

[1] Paper presented at the Princeton meeting of the Physical Society, October 23, 1909.

[2] Ann. der. Ph., Vol. 52, 1894, p. 433.

of this series,[1] the only modification being that the source S was replaced by a spectrometer, whose movable telescope arm T (see Fig. 1) carried the source of light, the spectrum of which was to be thrown on the sensitive surface of the photo-electric cell, through the fixed collimator tube A. The spectrometer was calibrated by the lines from a mercury vapor lamp, the slit of the collimator tube A being, for this purpose, replaced by an eye-piece. The prism gave a spectrum about eight degrees in width. The widths of the two slits were equal and represented about 10 minutes of arc.

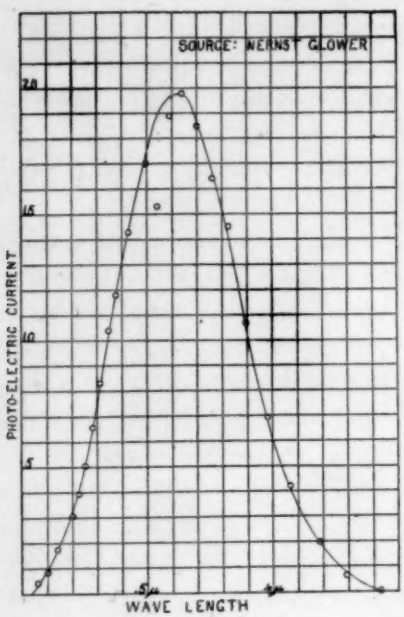

Fig. 2.

As before described,[1] the platinum wire leading to the sensitive surface was charged to such a negative potential as to reduce the leakage current, through the walls of the cell, to zero, thus making the photo-electric surface at zero potential with respect to the receiving Pt wire p. Under these conditions the rate of deflection of the electrometer as measured by a chronograph was proportional to the photo-electric current. Care was taken to adjust the screening so that there was no discharge when the source S was cut off.

A Nernst glower was at first used as a source at S. Although this furnished a very intense light the glowers did not last long enough on direct current for making a good set of observations, and no convenient means of regulation was at hand when the glowers were used on alternating current. However, as the Nernst glower formed a very satisfactory source, one run was made and is recorded here in Fig. 2. The ordinates are the observed photo-

[1] PHYS. REV., Vol. XXIX., 1909, pp. 71–80.

electric currents expressed as the rate of deflection of the electrometer, in mm./sec. No correction has been made for the variable dispersion of the prism or for the energy distribution in the spectrum of the Nernst glower.

As this curve is not very smooth, probably due to fluctuations in the alternating current voltage, it was thought best to substitute an acetylene flame. This had a twofold advantage. Not only was it of constant intrinsic brightness but also the energy distribution was known, having been recently determined by Professors Nichols and Merritt.[1]

In order to make the results useful for comparison two corrections were made: First, due to the variable dispersion of the prism, it was necessary to reduce the observed photo-electric currents to what would have been obtained had the spectrometer slit included a constant number of wave-lengths at each observation. The slit width was such as to make it possible to do this by graphical means from the slope of the calibration curve of the spectrometer. Second, the final relation between wave-length and photo-electric current should show the current that would be produced by the same amount of energy at each wave-length. This correction was made by dividing the observed currents by the relative energy for each wave-length in the spectrum of acetylene. As the above curve of Nichols and Merritt for the energy distribution extends only as far as .48 μ, while the observations in this experiment extend to .42 μ, the following method of extrapolation was used.[2]

Wien's equation for the energy distribution in the spectrum of a black body

$$E = c\lambda^{-5} \cdot e^{\frac{-\beta}{\lambda T}}$$

may be written in the form

$$\frac{1}{\lambda} = -\frac{T}{\beta}\log_e E\lambda^5 + \frac{T}{\beta}\log c$$

which is the form of a straight line, where $1/\lambda$ and $\log_e E\lambda^5$ are the

[1] PHYS. REV., Vol. XXX., p. 328.

[2] This method is perhaps not altogether justified since we are not sure that acetylene follows Wien's law of radiation exactly. It is used here, however, with the hope of checking it up later.

variables. These values were determined from the above mentioned energy curve, and plotted as a (nearly) straight line in Fig. 3. See data Table I.

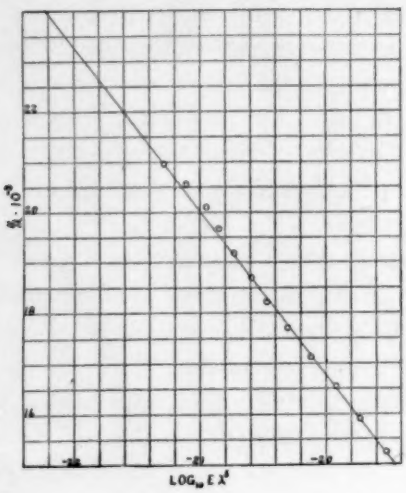

Fig. 3.

TABLE I.

$\lambda \cdot 10^4$	Relative Energy.	$\text{Log}_{10} E\lambda^5$	$\frac{1}{\lambda} \cdot 10^{-1}$
.656	24.76	−20.4782	1,525
.628	18.86	.2655	1,591
.604	14.88	.0776	1,654
.583	11.28	−21.8808	1,713
.565	8.65	.6970	1,769
.548	6.86	.5303	1,822
.534	5.90	.4083	1,870
.522	4.82	.2690	1,918
.509	4.20	.1547	1,967
.498	3.70	.0522	2,010
.487	2.84	−22.8888	2,055
.477	2.10	7.147	2,096

This line was extended as far as necessary toward shorter wavelengths and from it, by computation in reverse order, a new energy distribution curve obtained, extending to .42 μ. (See Fig. 4, *III.*) The column labeled energy in data Table II. is obtained directly from this curve. And the observed photo-electric currents, after

making the correction for variable dispersion are divided by these energy values. The resulting currents are those which would have been obtained from a normal spectrum containing the same amount of energy for each wave length. The results are shown in data Table II., and graphically in Fig. 4, curve *I* being the observed curve, and *II* the curve after making both the above corrections.

TABLE II.

$\lambda \cdot 10^4$	Slope of Calibration Curve.	Observed Rate of Deflection, mm./sec.	Rate of Deflection Corrected for Dispersion.	Relative Energy.	Final Corrected Photo-electric Current.
.685	2.90	.0252	.0087	28.0	.0031
.658	2.49	.0491	.0197	24.6	.0080
.635	2.15	.151	.0703	19.8	.0355
.614	1.89	.311	.1645	16.1	.1022
.596	1.69	.660	.390	13.1	.298
.579	1.51	1.012	.671	10.7	.627
.565	1.38	1.351	.980	8.95	1.095
.552	1.26	1.620	1.285	7.50	1.71
.540	1.16	1.840	1.588	6.27	2.53
.528	1.07	1.928	1.800	5.24	3.44
.518	.99	1.960	1.980	4.42	4.48
.508	.92	1.94	2.11	3.72	5.67
.499	.86	1.82	2.12	3.18	6.77
.491	.81	1.69	2.09	2.74	7.63
.483	.76	1.49	1.97	2.35	8.49
.475	.71	1.37	1.92	1.99	9.66
.462	.64	.955	1.49	1.49	10.00
.450	.57	.640	1.12	1.13	9.90
.440	.52	.394	.758	.89	8.52
.429	.47	.224	.477	.67	7.12
.420	.44	.106	.241	.52	4.64

Column 2: Determined graphically from calibration curve of spectrometer.
" 4: Column 3 divided by column 2.
" 6: Column 4 divided by column 5, with decimal point shifted.

The significance of the exact shape and location of this curve for sodium is not at present apparent. The maximum occurs at about $\lambda = .46\,\mu$ and yet $\lambda = .46\,\mu$ does not seem to bear any unique relation to any of the known properties of sodium. Still some relation must exist. There must be some reason why a sodium surface shows a maximum at one wave-length, and rubidium, for example,

at another. If such a relation could be established it would doubtless do much to explain not only photo-electric phenomena but also many questions connected with the structure of matter.

Whatever theory of the photo-electric discharge we accept the shape of the above curve is very strongly suggestive of resonance in some form or other and that the expulsion of the electron is due to selective absorption of light. If such is the case the free period of the electron in the sodium atom in its solid state should be determined by the period of vibration for $\lambda = .46\,\mu$ and metallic sodium ought to show selective absorption for this wave-length. But since the curve extends over a comparatively large range of frequencies, the question might be raised whether the frequencies of the electrons are correspondingly distributed, or whether all the electrons have the same frequency and the effect of light other than $\lambda = .46\,\mu$ is due to vibrations of a semi-forced nature. Further experiments along this line are in progress.

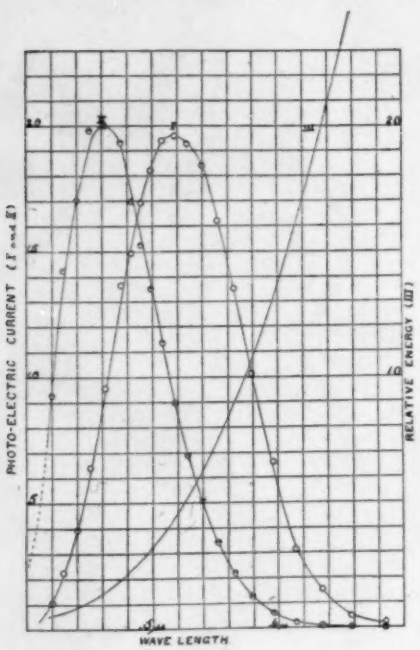

Fig. 4.

Apropos of the present discussion as to whether the energy of the expelled electron comes from an atomic explosion under the influence of light or from the absorption of energy from the incident light,[1] it might be of interest to consider the energy changes involved. Unfortunately data are available for only the roughest kind of an approximation, but the magnitude of the quantities concerned can at least be shown.

In a recent experiment by the writer[2] a sodium surface containing

[1] See article by Jakob Kunz, Phys. Rev., XXIX., p. 212.

[2] Phys. Rev., Vol. XXIX., p. 212.

10 square centimeters was exposed to the radiation from a 2,000 candle-power arc at a distance of something less than 1.5 meters. If we assume the reflecting power of sodium as given by Drude (for white light?) to be 99.7 per cent. we obtain, after making due allowance for other absorptions and reflections, that approximately 400 ergs per second of light energy are absorbed by the sodium surface. Comparing the above distribution curve with the visibility curve we might conclude that 100 ergs per second of this energy fall within those wave-lengths which are capable of producing the discharge.

The photo-electric current resulting was $25 \cdot 10^{-9}$ amperes, corresponding to $25 \cdot 10^{10}$ electrons per second if we accept the value of e as 10^{-20}. In the article cited Kunz has found the initial velocity of the electrons from a sodium-potassium alloy to be $6 \cdot 10^{7}$ cm./sec. for $\lambda = .42\ \mu$. The velocity of the electrons from the above sodium surface can hardly be more than $10 \cdot 10^{7}$ cm./sec., giving as the kinetic energy per electron $3 \cdot 10^{-12}$ ergs, where m is taken as $6 \cdot 10^{-28}$ grams. This makes the total kinetic energy of the expelled electrons .75 erg per second, a quantity which so far as its magnitude is concerned could easily be supplied from the 100 ergs per second of absorbed energy.

Since the above was prepared for publication, Hallwachs[1] has published some data showing the "specific photo-electric activity" for potassium from .2 μ to .6 μ, using the lines of the mercury arc in quartz as the exciting source. Excluding the existence of secondary maxima, his data, when plotted as a smooth curve, take the form shown in Fig. 5, *I*. It was suggested to the writer that the radical difference between this curve and Fig. 4, *II*, above, might have been in part due to the use of a flint glass prism, which undoubtedly did absorb some of the energy in the blue and violet region. It did not seem possible, however, that this absorption could have been sufficient to change Fig. 4, *II*, over into the form shown by the investigations of Hallwachs.

It is to be regretted that measurements of the energy distribution in the spectrum of acetylene in the neighborhood of .4 μ are almost impossible. However, to test in a qualitative way the influence of absorption, the flint glass prism was replaced by a carbon bisulphide

[1] Ann. d. Ph., XXX., p. 593.

prism, which is especially transparent to the blue and violet and the measurements repeated. The results are shown in data Table III., and graphically in Fig. 5, curves *II*, *III*, and *IV*. Curve *II* is plotted from the observed data as recorded in Table III., without making any corrections. The ordinates, as in Fig. 4, are rates of deflection of the electrometer in mm. per second. It is to be noted

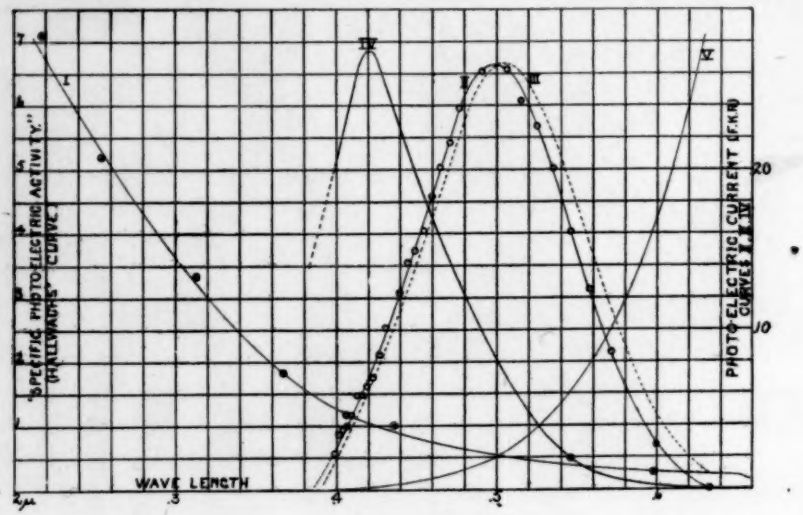

Fig. 5.

that the maximum ordinate is only a trifle over one tenth of the corresponding ordinate in Fig. 4, *II*. This is due to smaller light intensity. A slight correction to curve *II* is necessary on account of the rapid change of the index of refraction of CS_2 with change of temperature. Fig. 5, *III*, is the result of this correction, the points being omitted to avoid confusion. Finally, after reducing to a normal spectrum with equal energy distribution, we get Fig. 5, *IV*.

The maximum persists although, as might be expected, it is shifted somewhat toward shorter wave-lengths. Still it seems sufficiently prominent to call it a primary rather than a secondary maximum, the exact location of the crest being somewhat in doubt. In other words the use of the flint glass prism seems to have shifted the curve rather than changed its form.

TABLE III.

Wave-length.	Observed Photo-electric Currents.	Wave-length.	Observed Photo-electric Currents.
.6330 μ	.0000 mm./sec.	.4492 μ	.1492 mm./sec.
.5980	.0274	.4442	.1420
.5712	.0858	.4396	.1230
.5581	.1251	.4306	.1016
.5460	.1610	.4265	.0843
.5353	.2004	.4226	.0703
.5250	.2270	.4190	.0643
.5152	.2428	.4158	.0594
.5064	.2625	.4124	.0587
.4908	.2612	.4092	.0463
.4770	.2380	.4064	.0398
.4708	.2165	.4038	.0374
.4650	.2015	.4013	.0342
.4598	.1835	.3984	.0222
.4542	.1619		

In conclusion, the extreme sensibility of the photo-electric cell, even at zero potential, may be mentioned. In these later experiments, the shape and size of the CS_2 prism was such as to necessitate cutting down the beam of light through it to a few millimeters diameter. The light emerging from the collimator *A* (see Fig. 1), when allowed to fall on a piece of white cardboard, was scarcely visible even in a dark room. And yet the photo-electric currents produced by it were measured without much difficulty. This is more strikingly illustrated by reference to Fig. 5, *V*, which shows the relative energy for each wave-length falling on the cell, taking into account the variable dispersion of the prism.

CORNELL UNIVERSITY,
October, 1909.

SOME PHOTO-ELECTRIC PROPERTIES OF THE ALKALI METALS.

IV. LABORATORY APPLICATIONS.[1]

BY F. K. RICHTMYER.

WHILE performing some photo-electric experiments the writer was greatly impressed with the possibilities of putting this phenomenon to various laboratory uses where optical measurements by eye are either extremely difficult or altogether impossible. For example as a photometric device for monochromatic light a sensitive sodium surface excels the eye in several respects:

1. In a properly constructed cell there is absolutely no fatigue.

2. The greatest sensibility is in the blue and violet region, where the eye is least sensitive.

3. The magnitude of the photo-electric current, *i. e.*, the sensibility of the device, can be increased by (*a*) increasing the area of the sodium surface, (*b*) increasing the area of the photometric field, and (*c*) decreasing the distance of the field from the sensitive surface; whereas the action of the eye depends simply on the intensity of light in the photometric field. In a photometer little gain in sensibility results from increasing the size of field, or, within limits, of moving the field nearer the eye.

A case in point is the measurement of decay of phosphorescence. A sample of Balmain's paint on a visiting card was exposed to sunlight for thirty seconds, and then placed over a window about eight cm. in front of a sodium surface, so that 10 or 12 square centimeters of the card were exposed. At first the rate of deflection of the electrometer[2] was too rapid for accurate measurement. After about six minutes, however, observations were begun and the rate of

[1] Paper presented at the Princeton meeting of the Physical Society, October 23, 1909.

[2] For description of apparatus and adjustments see the first paper in this series, PHYS. REV., Vol. XXIX., pp. 71–80.

charge taken by chronograph about every four minutes, continuing for one hour after exposure. The results are shown in data table and graphically in Fig. 1 (I), in which the ordinates, while photo-

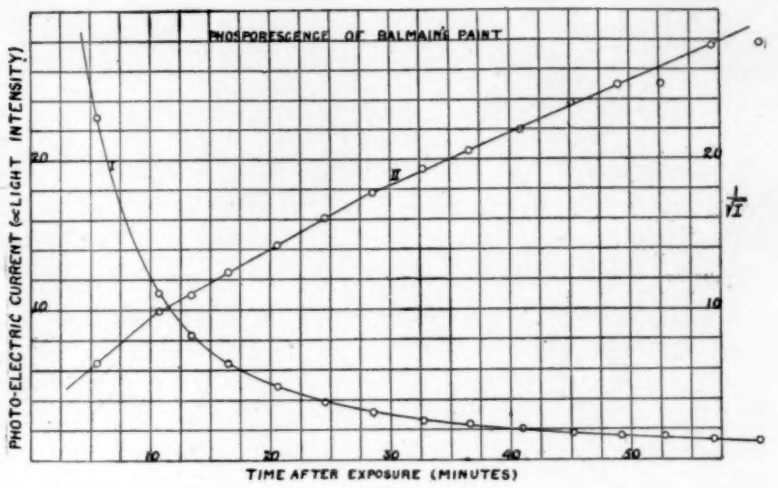

Fig. 1.

electric currents, are proportional to the intensity of light emitted by the phosphorescing paint.

TABLE I.

Time after Exposure.	Rate of Charge of Electrometer, Proportional to Intensity of Light.	$\frac{1}{\sqrt{I}}$	Time after Exposure.	Rate of Charge of Electrometer, Proportional to Intensity of Light.	$\frac{1}{\sqrt{I}}$
5.53 min.	2.29 mm./sec.	.65	36.65 min.	.236 mm./sec.	2.06
10.68	1.11	.95	40.95	.206	2.20
13.40	.829	1.10	45.18	.176	2.38
16.53	.641	1.25	49.15	.159	2.50
20.60	.489	1.43	52.83	.158	2.51
24.67	.385	1.61	56.88	.131	2.76
28.73	.316	1.78	60.7	.130	2.77
32.75	.259	1.96			

At the end of one hour the substance was just visible. Accurate measurements by the eye would have been practically impossible, whereas the electrometer was being deflected at a fairly

measurable rate — over .1 mm./sec. And this rate of deflection could have been increased many times had the exposed area of paint, and its distance from the cell been sufficiently altered. For example, a card 10 cm. square, placed 6 cm. from the cell would have increased the rate of deflection twenty times or more, *i. e.*, to 2 mm./sec. at the end of one hour, which would make observations possible for several hours.

When the above data are plotted in the usual manner, with $1/\sqrt{I}$ against time the curve shown in Fig. 1 (*II*) results. Except in a general way no great amount of importance should be attached to the compound linear character of this curve, as no special care was taken to eliminate or correct for the leakage currents (previously mentioned[1]) through the glass walls of the cell, the object being simply to test the cell as a photometric device and not the study of phosphorescence.

Another possible application results from the fact that the total quantity of electricity discharged from the sensitive surface, and therefore the permanent deflection given to the electrometer, depends on the integral $I \cdot dt$, where I represents the light intensity over an interval of time dt. That is, such a combination of cell and electrometer is to light measurements what the electrolytic cell is to the measurement of quantity of electricity. In this way the study of short decay phosphorescence might be possible. The writer has also made measurements of the relative total quantity of light passing through a photographic shutter set at speeds of .01, .02 and .04 sec. For this purpose the closed shutter, mounted in front of the cell, was illuminated by a beam of parallel light. The "exposure" was then made and the resulting deflection of the electrometer noted. Unfortunately these data were not preserved and it must suffice to say that in the case of .01 sec. the deflection was 20 or 30 mm.

Although possibly a little troublesome to work with, nevertheless it would seem that this phenomenon is capable of more extended laboratory use than has heretofore been made of it.

Cornell University,
October, 1909.

[1] Phys. Rev., Vol. XXIX., pp. 71–80.

THE TEMPERATURE OF THE DIVIDED BUNSEN FLAME.

By Daniel W. Shea.

IN the course of an experimental study of the electrical character of the source of light radiation made with a divided Bunsen flame, in this laboratory, by Dr. T. P. Irving,[1] it became desirable to know the temperature of the different parts of the flame, when in its simple state and when colored by burning in it various metal vapors. As the literature on this flame, so far as we could learn, contained no temperature records of service to us, I measured the temperature at numerous points. The measurements, though made only for the size and form of burner described below, yielded some results interesting in themselves and of importance in connection with Dr. Irving's work. The following pages contain a brief account of the apparatus and measurements, and some discussion of the results.

I. The Apparatus.

The burner used to separate the cones of the Bunsen flame consisted of a brass tube *a*, Fig. 1, 24 cm. long and 1.4 cm. wide inside, and a glass tube *b* shaped like that employed by Fredenhagen,[2] 15 cm. long, 4.8 cm. wide inside at the bottom and 2.7 cm. inside at the top. The glass tube was fitted over the brass tube by means of a bored plug of rubber, 3 cm. thick, inserted 1 cm. into the glass tube.

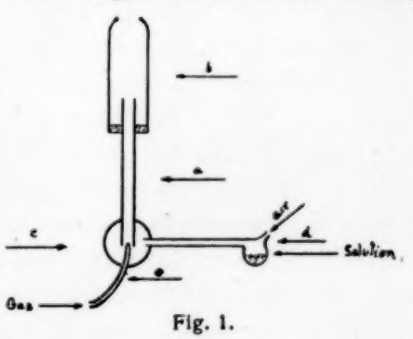

Fig. 1.

By sliding this plug up or down on the brass tube the distance betweeen the bases of the two cones could be varied at pleasure.

[1] Phys. Rev., XXIX., p. 243, 1909.
[2] Physik. Zeitschr., VIII., p. 404, 1907.

The device for mixing the gas, air and metal vapor for the burner consisted of a glass bulb *c*, Fig. 1, of 6 cm. internal diameter, bored at the top for receiving the lower end of the brass tube *a* of the burner, at the side for receiving the neck of a small retort *d* and at the bottom for the introduction of the gas tube *e*. The tube *e* was of glass with an internal diameter of 1.5 cm., but drawn out at the upper end so as to leave an opening only .08 cm. in diameter for the issuing of the gas. This drawn-out end extended up into the brass tube *a* a few millimeters. The retort *d* contained the solution for producing the metal vapor. Through its tubulure the necessary air was admitted. The tubes *a* and *e* and the neck of the retort were sealed hermetically with wax into the glass bulb.

This combination of burner and mixing device gave a steady divided Bunsen flame when the flow of air and gas was properly regulated.

The metal vapor was introduced by the Beckmann[1] method, which consists in putting an acid solution of a salt of the metal, together with some pieces of coppered zinc, into the retort, and allowing the air entering through the loosely stoppered tubulure to carry the metal vapor through the bulb *c* up into the tube *a* of the burner.

The thermometer was an Heraeus Pt-PtRh thermo-element connected with a Weston millivoltmeter. The wires were protected by 12-inch lengths of fire-clay tube near the junction, and their terminals were kept at the temperature of melting ice. The junction was globular, about 1 mm. in diameter. It was glowed by electric current to expel any occluded gases before beginning the measurements.

II. The Temperature Measurements.

These were made by inserting the junction of the thermo-element into the various parts of the outer cone, and through the outer cone, into the parts of the inner cone, and into the space between the two cones, reading the millivoltmeter as soon as steady temperature was indicated. The outer cone is so stable that its burning is not interfered with by thrusting through it the protected thermo-element. The inner cone is more sensitive to disturbance than is the outer

[1] Zeitsch. für Angewandte Chemie, p. 561, 1907.

cone, but it is not so sensitive as to make difficult the measurements of its temperature. Several observations were made for each part studied, and the mean of the millivoltmeter readings for each were converted into degrees centigrade by means of the Reichsanstalt certificate accompanying the thermo-element.

The divided flame in its simple state, that is, in the form of two conical shells of burning illuminating gas, was studied first, and for the distances 11, 8, 6 and 0 cm., respectively, between the bases of the cones. Then studies were made for the same distances when the divided flame was colored by burning in it the vapors of Na, Rb, Cs, Ca, Sr and Ba, produced from the solution of their respective chloride in the retort *d*. The outer conical shell in all cases rested directly upon the top of the glass tube *b*; the inner conical shell directly upon the top of the brass tube *a*, excepting for the distance near zero, when this shell shifted to the top of the glass tube *b*. The gas was taken from the gas mains of Washington.

The height of the outer cone was about 14 cm. and that of the inner cone about 1.75 cm. for all values of the distance between the bases of the cones.

1. *Temperature of the Outer Cone.*

Measurements were made at several points in the conical shell of flame at its base, then at several points in the shell at its intersection with a horizontal plane about 2 cm. above the base, again at the intersection with a plane about 4 cm. above the base, finally at the apex of the cone, 14 cm. above the base. The mean results are given in centigrade degrees in the Tables I.–IV. The grayish color

TABLE I.

Distance between the Bases of the Cones, 11 *cm.*

	At Base.	At 2 cm.	At 4 cm.	At Apex.
Simple flame	563.7	743.8	823.4	884.1
Colored by Na	699.1	793.3	893.1	904.3
Rb	647.8	788.4	881.8	906.1
Cs	629.9	768.2	828.1	901.8
Ca	623.6	753.7	830.1	884.1
Sr	563.7	703.9	803.6	893.1
Ba	647.8	783.2	846.2	897.4

of the outer cone of the simple flame changes to that characteristic of the metal when a metal vapor is introduced. There was so little change in the temperature from about 4 cm. to the apex, and that so regular that measurements made between those points are omitted from the tables.

TABLE II.

Distance between the Bases of the Cones, 8 *cm.*

	At Base.	At 2 cm.	At 4 cm.	At Apex.
Simple flame	614.9	782.6	829.3	891.5
Colored by Rb	716.1	801.8	884.1	910.4
Ca	648.3	770.3	890.1	919.1

Measurements for the simple flame and for Rb and Ca only are given in Table II. and the two following tables, since they are sufficient to show how the temperature varies with variation in distance.

TABLE III.

Distance between the Bases of the Cones, 6 *cm.*

	At Base.	At 2 cm.	At 4 cm.	At Apex.
Simple flame	653.6	793.6	890.4	939.9
Colored by Rb	751.8	873.2	947.9	966.7
Ca	716.9	844.5	927.8	965.2

TABLE IV.

Distance between the Bases of the Cones, 0 *cm.*

	At Base.	At 2 cm.	At 4 cm.	At Apex.
Simple flame	704.0	837.7	937.3	968.2
Colored by Rb	730.4	969.8	993.1	990.0
Ca	880.1	973.6	1,013.0	1,002.5

2. *Temperature of the Inner Cone.*

Measurements were made, as for the outer cone, at the base, at about 0.5 cm., 0.9 cm., 1.3 cm., and at the apex. The results are given in degrees centigrade in Tables V.–VIII. The results for Rb and Ca only will be given in Tables VI.–VIII. The inner cone retains always its greenish color. A solid colored flame burns just above it, characteristic of the metal introduced.

TABLE V.

Distance between the Bases of the Cones, 11 *cm.*

	At Base.	At 0.5 cm.	At 0.9 cm.	At 1.3 cm.	At Apex.
Simple flame	996.5	1,024.6	1,045.2	1,058.9	990.0
Colored by Na	1,000.0	1,048.1	1,090.0	1,085.0	1,000.0
Rb	988.6	1,009.9	1,048.1	1,023.0	988.6
Cs	1,015.8	1,034.3	1,056.6	1,083.3	997.4
Ca	987.3	1,012.7	1,021.4	1,029.3	980.0
Sr	990.0	1,006.4	1,042.9	1,053.2	980.0
Ba	988.6	1,017.0	1,042.2	1,047.0	997.4

TABLE VI.

Distance between the Bases of the Cones, 8 *cm.*

	At Base.	At 0.5 cm.	At 0.9 cm.	At 1.3 cm.	At Apex.
Simple flame	998.9	989.6	1,049.9	1,057.2	993.7
Colored by Rb	997.4	1,028.9	1,047.6	1,038.1	988.6
Ca	1,000.0	1,051.3	1,085.0	1,050.0	988.6

TABLE VII.

Distance between the Bases of the Cones, 6 *cm.*

	At Base.	At 0.5 cm.	At 0.9 cm.	At 1.3 cm.	At Apex.
Simple flame	996.2	1,000.7	1,011.1	1,027.9	980.0
Colored by Rb	995.2	1,017.3	1,023.8	1,034.1	988,6
Ca	1,006. 0	1,047.1	1,062.7	1,037.3	980.0

TABLE VIII.

Distance between the Bases of the Cones, 0 *cm.*

	At Base.	At 0.5 cm.	At 0.9 cm.	At 1.3 cm.	At Apex.
Simple flame	732.5	821.3	950.9	973.2	998.6
Colored by Rb	730.4	839.8	965.2	992.0	1,013.3
Ca	880.1	830.6	958.9	987.7	1,008.4

3. *Temperature Along the Axis of the Burner.*

Measurements were made from the apex of the inner cone, at intervals of 1 cm., up along the axis of the burner, to the base of the upper cone, and at the center of the axis of the upper cone. The results are given in centigrade degrees in Tables IX.–XII. The results for Rb and Ca only will be given in Tables X.–XII.

The part of the axis just above the apex of the inner cone is, for the colored flames, in the solid flame of burning metal vapor which rests on this cone, and extends above its apex. The length of the flame is about the same for the various elements, Sr excepted, and for the various distances between the bases of the cones.

The length of these flames of burning metal vapor, measured from the tip of the cone, were about as follows:

Na-flame, 8.0 cm.; Rb-flame, 9.5 cm.; Cs-flame, 8.5 cm.; Ca-flame, 8.0 cm.; Sr-flame, 3.0 cm.; Ba-flame, 8.5 cm.

TABLE IX.

Distance between the Bases of the Cones, 11 *cm.*

	Distance in cm. above Apex of Inner Cone.										
	0	1	2	3	4	5	6	7	8	9	16
Simple flame	990.0	965.9	935.7	910.4	880.1	840.2	788.4	752.7	717.0	703.5	793.3
Colored by Na	1,000.0	972.7	972.7	951.4	937.8	909.1	882.0	893.1	788.4	727.0	793.2
Rb	988.9	972.7	965.9	953.9	935.7	910.4	884.1	860.1	832.5	727.0	788.4
Cs	997.4	972.7	965.9	953.9	932.2	901.8	867.8	832.5	793.3	735.3	815.2
Ca	980.0	972.7	965.9	953.9	927.8	884.1	860.1	832.5	793.2	744.3	788.4
Sr	980.0	972.7	965.9	910.4	860.1	823.2	806.3	793.3	788.4	735.3	727.0
Ba	977.4	972.7	965.9	953.9	945.4	927.8	893.1	867.8	814.9	727.0	762.6

The point on the axis at the distance 9 cm. above the apex of the inner cone coincides with the center of the base of the outer cone; the point at distance 16 cm. with the central point of the axis of the outer cone.

TABLE X.

Distance between the Bases of the Cones, 8 *cm.*

	Distance in cm. above Apex of Inner Cone.							
	0	1	2	3	4	5	6	13
Simple flame	978.5	967.3	950.1	931.2	926.0	874.6	761.5	803.9
Colored by Rb	988.6	972.7	965.9	953.9	935.7	901.8	788.4	806.3
Ca	980.0	972.7	965.9	953.9	927.8	884.1	746.3	806.3

The point on the axis at 6 cm. above apex of the inner cone coincides with the center of the base of the outer cone; the point at 13 cm. with the central point of the axis of the outer cone.

TABLE XI.

Distance between the Bases of the Cones, 6 *cm.*

	Distance in cm. above Apex of Inner Cone.					
	0	1	2	3	4	11
Simple flame	980.0	965.9	884.6	840.2	788.4	832.5
Colored by Rb	988.6	972.7	953.9	932.2	822.3	849.6
Ca	980.0	972.7	965.9	945.6	840.2	867.8

The point on the axis at 4 cm. above apex of inner cone coincides with the center of the base of the outer cone; the point at 11 cm. with the central point of the axis of the outer cone.

TABLE XII.

Distance between the Bases of the Cones, 0 *cm.*

	Distance in cm. above Apex of Inner Cone.			
	−1.75	−1	0	5.25
Simple flame	247.9	471.8	984.1	1,061.6
Colored by Rb	258.5	498.7	997.4	1,070.9
Ca	250.0	483.2	972.7	1,013.5

The point on the axis at − 1.75 cm. from the apex of the inner cone coincides with the center of the common base of the two cones; the point at 5.25 cm. coincides with the center of the axis of the outer cone, and is in the metal flames.

Measurements of the temperature of the solid flame of burning metal vapor which rests on the inner cone were made at various distances from the axis, and they indicated a slight falling off of the temperature as the distance from the axis increased. Thus for the Sr-flame, at a point opposite the apex of the inner cone and just within the surface of the flame, the temperature was 972.7 when it was 980.8 at the axis as given in Table IX.; and it was 935.7 at a point opposite that on the axis 1 cm. above apex at which axial point the temperature was then 972.7, as given in Table IX.

4. *Temperature at Points Outside the Axis.*

Measurements were made at numerous points other than those given in the preceding subsections. Tables XIII.–XV. contain the

results for points at about 0.5 cm. distant from the inner surface of the glass tube *b* and from the top of the plug to the top of the glass tube.

TABLE XIII.

Distance between the Bases of the Cones, 11 *cm.*

	Distance in cm. above Top of Plug.				
	0	3	5	9	14
Simple flame	288.5	450.9	569.1	631.8	653.7
Colored by Na	258.5	425.8	471.8	499.0	554.6
Rb	444.5	544.5	644.5	699.1	752.7
Cs	288.5	471.8	554.6	635.8	725.4
Ca	415.8	453.7	528.2	663.7	790.0
Sr	288.5	480.9	571.8	644.5	663.7
Ba	329.8	429.8	499.0	553.6	635.8

The point 5 cm. above top of plug is opposite apex of inner cone; the point 14 cm. is at the base of the outer cone.

TABLE XIV.

Distance between Bases of the Cones, 8 *cm.*

	Distance in cm. above Top of Plug.				
	0	3	5	8	14
Simple flame	361.4	560.1	703.8	719.3	767.5
Colored by Rb	338.2	535.4	671.2	725.4	788.4
Ca	355.7	544.5	671.2	780.0	788.4

The point 8 cm. is opposite the apex of the inner cone; the point 14 cm. is at the base of the outer cone.

TABLE XV.

Distance between Bases of the Cones, 6 *cm.*

	Distance in cm. above Top of Plug.				
	0	3	5	10	14
Simple flame	379.1	583.2	698.6	825.4	819.9
Colored by Rb	355.7	562.7	663.7	814.9	822.3
Ca	385.5	599.0	725.4	822.3	840.2

The point 10 cm. is opposite the apex of the inner cone; the point 14 cm. is at the base of the outer cone.

III. Analysis of the Results.

Tables I.–IV. show that: (1) The temperature of the outer conical shell in all cases increases rapidly from the base to about two thirds way up the cone, then falls more rapidly to the apex, so that, if represented graphically, taking temperatures as ordinates and distances above the base as the abscissæ the curve is as shown in Fig. 2, *a*; (2) the temperature of the outer cone is somewhat greater for the

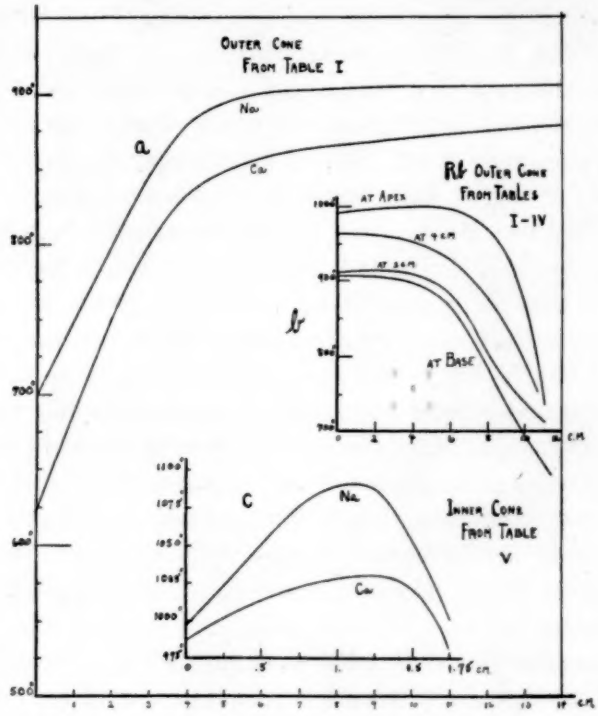

Fig. 2.

colored flame than for the simple flame, the differences being greater near the base, where they average, for Table I., about 75°, while near the apex they average only 30°; (3) the temperature of all parts of the outer cone for all cases is greater the shorter the distance between it and the inner cone. If the temperature for a given part of a given outer cone be plotted taking the temperature as ordinates and the distance between the bases of the cones as

abscissæ, the curve is as represented in Fig. 2, *b*, which shows the curves for Rb at apex, at 4 cm. point, at 2 cm. point and at the base; (4) the temperature of the outer cone seems to be somewhat greater for the elements of the first Mendeléeff group than for those of the second group, when the distance between the base of the cone is considerable; the reverse is the case when the distance becomes small.

Tables V.–VIII. show that: (1) The temperature of the inner conical shell for the simple and the colored flames and for distances between the bases of the cones not near zero increases from the base to a maximum value in a zone about 3 or 4 mm. broad, just above the middle of the cone, then decreases to a value at the apex which is about the same as at the base. These maxima for Table V. average about 70° higher than the minima. Near the zero of distance between the bases of the cones, the temperature distribution for the inner cone becomes similar to that of the outer cone, and the values are smaller than for longer distances. Fig. 2, *c*, shows the temperature curve for the inner cone when the distances between the cones are large; (2) the temperature of corresponding parts of the inner cone for the simple flame and for all the colored flames has practically the same value for all distances between the bases of the cones. As noted elsewhere in this paper, the characteristic greenish color of the inner cone for the simple flame remains unchanged through the burning of metal vapor, while that of the outer cone is changed, and a characteristic solid flame of the metal vapor appears between the two cones.

A comparison of Tables I.–IV. with V.–VIII. shows that the temperature of the inner cone is higher than that of the outer cone until the distance between the bases of the cones is nearly zero. Then the outer cone becomes the hotter, and the hottest point of the flame, which is then the ordinary Bunsen flame, is above the apex of the inner cone and near the center of the outer cone. The highest temperature found there, 1070.9°, occurred when burning Rb vapor. The highest temperature of the flame of an ordinary Bunsen burner using the same gas was found at about the same distance above the inner cone as in the case just mentioned, and it had the value 1186.6°, the mean of a large number of observations. The

temperature near the base of the same flame measured 361.3° and was the lowest temperature found in that flame. A comparison of all the Tables I.–XV. shows that the highest temperature attained in the divided Bunsen flame is that of the zone of the inner cone just above its middle. The highest temperature found there, 1090.0°, occurred at the time the flame was burning Na-vapor (see Table V.). In Fig. 3, *a*, the two cones and the flame of burning metal vapor are shown, and in Fig. 3, *b*, this zone of highest temperature is indicated by the heavy parts of the lines.

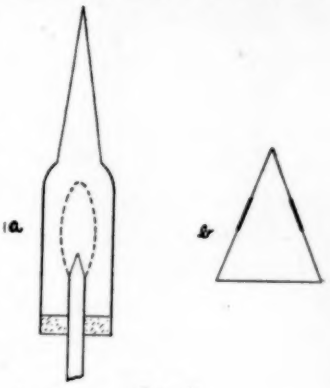

Fig. 3.

Tables IX.–XII. show that: (1) The temperature along the axis of the burner decreases regularly up to the base of the upper cone, then increases to the apex of the upper cone; (2) the temperature is about the same for the corresponding points of the first three centimeters of this axis for all the colored flames, and is only slightly larger in the average than that for the simple flame. At points higher up the temperature differs considerably for the different flames, and averages for the colored flames considerably higher than for the simple flame, until the base of the outer cone has been reached; (3) the temperature for the simple and for the colored flames remains about the same for each corresponding point of the axis below the outer cone, as the distance between the bases of the cones is shortened, but it increases rather rapidly in the outer cone; (4) the temperatures for the elements of the first Mendeléeff group average about the same as for the elements of the second group.

Tables XIII. to XV. show: (1) At points in the space outside the inner cone, and outside the flame between the cones, the temperature increases considerably as the distance between the bases of the cones decreases; (2) for any given point it is practically the same for both simple and colored divided Bunsen flames.

IV. SUMMARY.

The most interesting results of the measurements are these: (1) The highest temperature in a divided Bunsen flame is confined sharply to a small zonal segment of the inner conical shell, no matter what substances are used to color the flame, nor what the distance is between the bases of the cones, provided that that distance is at least a few centimeters; (2) the temperature of the inner conical shell is not changed by varying its distance from the outer conical shell, provided that the distance is more than two or three centimeters, nor by introducing through it metal vapors that burn in a flame above it and in the outer cone; (3) the temperature distribution of the inner conical shell changes to one that increases from base to apex when the distance between the cones approaches zero; (4) the temperature of the flames of metal vapor burning just above the inner cone is the same for all the vapors used, excepting near the tips of these flames, and it is not changed by varying the distance between the cones; (5) the temperature of the outer conical shell increases from the base to the apex and it is always greatest at the apex; (6) the temperature of the outer conical shell increases when its distance from the inner cone decreases; also when it burns metal vapors introduced through the inner cone.

V. RELATION TO IRVING'S RESULTS.

Irving found the negative electrical wandering of the inner cone stronger than that of any other part of the divided Bunsen flame, so strong that it "was torn off the brass tube on the side towards the negative plate" even by weak fields. The temperature measurements show that this inner cone is much the hottest part of the divided Bunsen flame. There are no distortions of the inner cone, in an electrical field, definite enough in location to say that they are at the hottest zone. The wandering was about the same for all distances between the bases of the cones. The temperature of the inner cone is also the same for all distances between the cones, if the distances are not too small. The magnitude of the negative wandering of the flames of metal vapor burning just above the inner cone Irving found to be the same for all the metals and for all distances between the cones. The tempera-

ture of these flames is the same for all the metals and for all distances between the cones. The electrical wandering of the flames towards the negative plate is less violent than is that of the inner cone. The temperature of these flames is less than that of the inner cone.

Irving found no wandering of the simple outer cone, nor for this cone colored with Li, but he found wandering towards the negative plate, when the cone was colored by the other metals, ranging from 9° for Na to 45° for Ca and Ba. The temperature of the simple outer cone is less than that of the inner cone and of the flame, for like conditions, ranging from about 100° to 500° cooler for different parts. Its temperature is higher when burning metal vapor than when in the simple state.

In Irving's experiments it was found that the outer cone wanders as soon as the metal flame burning above the inner cone reaches it, on decreasing the distance between the cones. Table IV. shows that the outer cone is then at its highest temperature.

The foregoing comparisons would indicate that the electrical wandering of the parts of the Bunsen flame is greatest for the hottest parts. This does not hold, however, for the metal vapor before it enters the inner cone. Its temperature there is about that of the room, yet it is even more electro-positive than is the hot inner cone. Further it does not hold in all respects for outer cones when compared with one another, for, although the temperatures given in Table I. for Ca, Sr and Ba are in the same order, excepting at the apex of the cone, as that given by Irving for the respective electrical wanderings, yet the temperatures for Na, Rb and Cs, excepting at the apex, are in an order the reverse of that given by him for the electrical wanderings. Futher the temperature given for Rb and Ca in Tables II. and III. are in an order the reverse of that for the electrical wanderings, while the temperatures given for the same elements in Table IV. are in the same order as that of the wanderings. Nevertheless, the parts having the higher temperatures show the larger electrical wanderings for any given divided Bunsen flame, whether it be a simple flame, or one colored by any one of the elements studied.

The correspondence of magnitudes of electrical wanderings and

magnitudes of respective temperatures may be mere coincidences, not due to any relationship of the two phenomena. But it seems probable that the changes in magnitudes occur simultaneously in the same direction necessarily. Irving offers an explanation of the decrease in the magnitude of the electrical wandering on passing from the inner to the outer cone, by supposing that the negative electrons from the cones neutralize the positive metal ions in the formation of oxides, which takes place chiefly in the flame above the inner cone. The formation of oxides would also explain the observed differences in the temperatures of the inner cone, metal flame and outer cone, if we suppose, as we must, that the parts are hottest where the oxidation is most extensive. The oxidation in the metal flame above the inner cone takes place to such an extent for all the metals studied that the flame is equally positive for all of them. At the same time the extent of oxidation is such that the flames are equally hot for all these metals.

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Physical Laboratory,
The Catholic University of America,
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THE RELATIVE MOTION OF THE EARTH AND THE ETHER.[1]

BY H. A. WILSON.

IT is shown in this paper that the aberration of light and the negative results of the experiments made to detect the relative motion of the earth and the ether can be explained without supposing that bodies change in length when they are set in motion relatively to the ether. The theory proposed is a modification of Sir G. G. Stokes' theory according to which the ether is regarded as behaving for differentially irrotational motions like an incompressible perfect fluid. The ether near an atom is supposed to be in irrotational motion as though the atom contained a point source of ether and an equal point sink so that the ether going into the atom at the sink comes out again at the source. The atoms consequently behave like hydrodynamical doublets. If preferred each atom may be supposed to contain many such doublets instead of only one. It is well known that sources and sinks in hydrodynamics are analogous to positive and negative charges in electrostatics. Thus matter containing hydrodynamical ether doublets is analogous to matter containing electrical doublets. High specific inductive capacity can be explained by supposing matter to contain electrical doublets which are polarized by an electric field and in the same way matter containing ether doublets will possess an analogous hydrodynamical property which may be called etherial permeability. The stream lines near a piece of matter placed in a stream of ether will be similar to the lines of electric force near a similar piece of insulator placed in a similar electric field provided the specific inductive capacity of the insulator is equal to the etherial permeability of the matter. The velocity potential of the etherial motion corresponds with the electric potential in the corresponding electrostatic case and so is a single valued function both inside and outside matter.

[1] Abstract of a paper presented at the Boston meeting of the Physical Society, December 28–31, 1909.

It is easy to prove that the supposed motion of the ether will not have any first order optical effects provided the influence of relative motion between matter and ether on the velocity of light in the matter postulated by Fresnel and verified by Fizeau is assumed.[1] The phenomena of aberration will therefore be the same as though the ether were at rest and the spectroscopic determination of star motion in the line of sight will also be unaffected by the supposed irrotational motion.

If we regard the matter forming the bulk of the earth as having a high etherial permeability the stream lines at the earth's surface will be nearly vertical (where the surface is horizontal) so that in experiments like Michelson and Morley's in which the apparatus is turned about a vertical axis a negative result will be obtained. A space inside matter will be partly screened off from the etherial stream just as the interior of a piece of iron is screened off from a magnetic field.

The rotation of a piece of matter about an axis of symmetry will not set the ether near it in motion. This agrees with Sir O. Lodge's negative result.

The theory described appears to offer a simple explanation of all available facts so that some new crucial experiment appears to be necessary to decide between it and the theory of a stagnant ether which is unmoved by moving matter.

It is necessary to suppose that the density of the ether is very small because otherwise there would be appreciable forces acting on pieces of matter placed in the etherial stream. If all matter has a high etherial permeability it may be extremely difficult to detect the supposed motion even by experiments capable of detecting second order effects because the etherial stream will be partly screened off by the stands supporting the apparatus.

It seems possible that optical and electrical phenomena depend on rotational motion and elasticity of the ether and so are very little influenced by irrotational motions. If the ether is really stagnant it is difficult to see how any phenomena can take place in it.

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THE NITROGEN THERMOMETER FROM ZINC TO PALLADIUM.[2]

BY ARTHUR L. DAY AND ROBERT B. SOSMAN.

THE investigation of the fundamental high temperature scale with the nitrogen thermometer, which was begun in the Geophysical Laboratory in 1904 and upon which a preliminary report was given to

[1] See for example Æther and Matter, by Sir J. Larmor.

[2] Abstract of a paper presented at the Boston meeting of the Physical Society, December 28–31, 1909.

the Physical Society at the Washington meeting in 1907[1] is now completed up to the temperature of melting palladium. A description of the apparatus is contained in a more extensive preliminary report published in the American Journal of Science in November, 1908.[2] The investigation has yielded an instrument: (1) in which the sensitiveness can be varied within considerable limits; (2) in which no zero change greater than the errors of observation occurs up to temperatures of 1550°; (3) in which all the well-known errors of earlier gas thermometry are reduced to about one fourth of their former magnitude; (4) in which the metal of the bulb (80 parts platinum, 20 parts rhodium) has very little contaminating effect upon the thermoelement used to transfer its temperatures to the standard melting points. The melting points, determined with this apparatus, of the pure substances commonly used as standards in high temperature measurements, are contained in the following table, together with the electromotive forces in microvolts of the standard (Pt 90, Rh 10) thermoelement.

	t		E
Cadmium	320.0°	±0.3°	2504
Zinc	418.2	±0.3	3429
(Interpolation Point) .	524.9		4470
Antimony	629.2	±0.5	5530
(Interpolation Point) .	854.1		7929
Silver	960.0	±0.7	9113
Gold	1062.4	±0.8	10295
Copper	1082.6	±0.8	10534
(Interpolation Point) .	1206.4		12000
(Interpolation Point) .	1298.5		13100
Diopside	1391.2	±1.5	14228
Nickel	1452.3	±2.0	14977
Cobalt	1489.8	±2.0	15439
Palladium	1549.2	±2.0	16143

A quadratic equation of the form $E = -a + bt + ct^2$ passed through the melting points of zinc, antimony and copper, reproduces all temperatures within this region with an accuracy equal to that of the absolute measurement. A similar curve passed through copper, diopside and palladium reproduces the upper region equally well. To write an interpolation formula for the entire curve requires a cubic of the form $E = -a + bt + ct^2 - dt^3$, and is much more cumbersome to handle. The extrapolation upward of the zinc-antimony-copper curve (which has been common practice for several years) gives a temperature 19° too low at the melting-point of palladium.

[1] J. K. Clement, PHYS. REV., 24, 531, 1907.

[2] Day and Clement, Am. Jour. Sci. (4), 26, 405, 1908.

There appears to be no prohibitive difficulty in the way of continuing the scale beyond 1550° if necessity arises. The greatest existing uncertainty is in the distribution of temperature over the surface of the bulb which amounts to about 2° at 1500°.

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